Studies on the biology of juvenile European eels (*Anguilla anguilla* L.)
in Irish rivers

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Abstract

Over the past three decades recruitment of European eel (Anguilla anguilla L.) to inland waters has declined by more than 95%. The causes of this decline are still unclear although a number of factors are thought to have a contributory effect including pollution, habitat loss, climatic changes in the ocean, overfishing and the spread of non-indigenous parasites and disease.

In this study, undertaken from 2008 to 2010, the abundance, timing and seasonal duration of eel recruitment was investigated on the Shannon, Erne and Lee river systems, where the natural connectivity of these rivers is interrupted by hydroelectric dams and regulating weirs. Catches of juvenile eels at fixed traps downstream of these structures were monitored and the length, weight and age of eels sampled were analysed. Total catch varied between years at each site and were generally low. The timing of the migration showed considerable interannual variability as well as differences between sites. Mean eel length was greater for eels trapped further upstream from the tidal limit of estuaries. At the Parteen regulating weir on the River Shannon variation in the juvenile eel catch was analysed in relation to environmental factors using multiple regression appropriate to time series data. Factors included in the regression model which explained a statistically significant portion of the variation in juvenile eel catch were: day length, flow, water temperature, moon fullness and year. An exceptional peak in the eel catch was recorded in August 2008 following very heavy rainfall. The catch recorded during August 2008 accounted for 51% of the total catch for the period 2008 to 2010.

Juvenile eels sampled at fixed traps were examined for the presence of Anguillicoloides crassus, an introduced Asian parasitic nematode of eels that can affect swimbladder function. Investigations on the infection levels in yellow and silver eels are frequently reported but there is a paucity of information regarding infection of juvenile eels. Prevalence and intensity of infection was determined. Relationships between host length and condition and the infection intensity were also investigated. Juvenile eels
sampled from the River Lee (N = 73) were found to be uninfected. Prevalence recorded for a sample from the Erne (N = 44) was 14% and mean intensity of infection was 1.0. On the River Shannon, samples (N = 498) were collected at the Ardnacrusha dam and Parteen regulating weir during 2008, 2009 and 2010. At Ardnacrusha elvers were more frequent in the trap catch and mean prevalence ranged from 23–66% with mean intensity ranging from 1.35 to 1.94. At Parteen, where larger juvenile eels are predominant in the trap catch, mean prevalence ranged from 59–66% and mean intensity ranged from 1.90 to 2.00. There was no significant correlation between the number of Anguillicoloides present and the condition factor of the eels sampled. Anguillicoloides infection of migrating juvenile eels used for stocking represents a mechanism of dispersal for the parasite to upstream habitat.

Measures to mitigate the effect of hydroelectric dams and regulating weirs on juvenile eel migration include implementation of trap and transport programmes. Evaluation of trap efficiency is a necessary step in improving the effectiveness of these programmes. In this study the size selectivity of traps with different substrate types was investigated at the Parteen regulating weir. Brush substrates of varying densities were shown to facilitate the capture of a wider size range of migrating eels. The importance of the location of a trap to its effectiveness was also demonstrated. Mark and recapture experiments were conducted at the Parteen regulating weir using visible implant elastomer (VIE) marking. Recapture rates of marked eels (N=1814) ranged from 0–16.25% and varied depending on release location. This low and variable recapture rate reflects the variable tendency to migrate exhibited by juvenile eels and the importance of the location of a trap to its effectiveness. Juvenile eels entering the trap at the Parteen regulating weir were monitored by closed-circuit video over three consecutive 24 hour periods. A pronounced diel pattern in activity was observed with 98% of juvenile eels entering the trap between dusk and dawn.
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Chapter 1  Introduction

Eels belong to the order Anguilliformes and to the sub-order Anguillidei. They are characterised by a snake-shaped body, dorsal and anal fins continuous with the caudal fin, atrophy of the pelvic fins and a leaf shaped larva called the leptocephalus. They are strictly marine, except for the Anguillidae family, which are amphihaline. The Anguillidae family has a single genus, *Anguilla* Schrank, 1798 (Lecomte-Finiger, 2003).

1.1  *Anguilla*

The freshwater eels of the genus *Anguilla* Schrank consist of 19 species/subspecies and are found in most tropical, subtropical and temperate areas except for the South Atlantic and the west coasts of North and South America (Watanabe, 2003; Aoyama, 2009). Fourteen species are found in the Indo-Pacific region, the most recently identified species being *Anguilla luzonensis* in the Philippines (Watanabe *et al.*, 2009). There are only two species in the North Atlantic: the European eel, *Anguilla anguilla*, and the American eel, *Anguilla rostrata*. Both species spawn in the Sargasso Sea but are considered separate species due to differences in morphometric and genetic traits. It is thought that the divergence of the two species represents a recent split in the evolutionary history of the genus *Anguilla* (Avise *et al.*, 1986; Bastrop *et al.*, 2000). Phylogenetic studies (Aoyama *et al.*, 2001) also suggest a descendent-ancestor relationship between Atlantic and Pacific eels respectively. The genus *Anguilla* originated about 65 million years ago in the Tethys Ocean, an ancient ocean that connected present areas of the Atlantic Ocean with the Indo-Malaysian area (Lecomte-Finiger, 2003). The existence of eels is known from fossils found in sediments of the Tethys from the Cretaceous to the Miocene periods and the eel population of that time was split by geologic events that led to the creation of the Indian and Atlantic Oceans (Tesch, 2003).
Distribution
According to the Schmidt (1909) the European eel (*Anguilla anguilla*) is distributed “from the North Cape in northern Norway and southwards along the coast of Europe, on all the coasts of the Mediterranean… and on the north-western part of the coast of Africa”. Iceland, Madeira and the Azores are also included. The Canary Islands are the most southerly collection point to date (Tesch, 2003). Within this distribution area (Figure 1.1) there is a large variation in the density of the eel stock. Major concentrations of glass eels recruiting from the ocean did and do occur in France and Spain and the highest productivity of coastal and inland waters occurs in areas bordering the western Mediterranean (Dekker, 2003a).

![Figure 1.1 Distribution of the European eel, *Anguilla anguilla* (FAO, 2011)]
Chapter 1

**Lifecycle**

The lifecycle of the European eel, *Anguilla anguilla* is unusual and remarkable in its complexity and duration. It has two distinct phases; the oceanic larval period and the continental growing period, which refers to the fish’s residency in coastal or inland waters. It is a complicated lifecycle that involves two metamorphoses and two transoceanic migrations and depends strongly on oceanic conditions for maturation, migration, spawning, larval transport and recruitment (van Ginneken and Maes, 2005).

Early surveys in the North Atlantic Ocean were carried out by Danish biologist Dr. Johannes Schmidt in the early 1900s to uncover the mystery of the location of the spawning grounds of the eel. The survey led to the collection of small leptocephali larvae in the Sargasso Sea (Schmidt, 1923). Subsequent surveys of the area conducted by McCleave and Tesch in the 1980s discovered an increase in small leptocephali less than 10 mm in length confirming the theory of the Sargasso Sea being the spawning ground. The American eel, *Anguilla rostrata* is also believed to spawn in the Sargasso Sea; however, like the European eel neither an adult eel nor eggs have been positively identified on the spawning grounds. The European eel has a long outward and return migration of approximately 6000 km compared to the 2000–3000 km distance covered by the American eel.

In 1856 a transparent, willow leaf-shaped fish from the Strait of Messina in the Mediterranean was discovered, which was called *Leptocephalus brevirostris* because of its small and slender head (Kaup, 1856). Forty years later Grassi and Callandruccio (1897) correctly identified the Leptocephalus as the larval stage of the river eel. These leptocephalus larvae are thought to be transported to continental Europe by passively drifting in the Gulf Stream and North Atlantic current (McCleave *et al.*, 1998). The duration of the migration of the leptocephali is not definitively known (McCleave *et al.*, 1998) and has been estimated to take 7 to 9 months (Lecomte-Finiger, 1994; Arai *et al.*, ...
or 14 to 16 months (Wang and Tzeng, 2000) based on unvalidated age determinations (Cieri and McCleave, 2000).

Leptocephalus larvae metamorphose into “glass eels” in coastal waters. The continental slope represents the boundary for the larvae (Antunes and Tesch, 1997). Glass eels take on the external form of the adult eel but lack pigmentation and appear transparent, hence the term glass eel. During estuarine migration they use selective tidal stream transport (STST) until they reach the tidal limit of the estuary (McCleave and Wippelhauser, 1987). This migratory behaviour involves the glass eels ascending the water column at the beginning of the flood tide and maintaining their position in order to migrate with the current. Then during ebb tides the glass eels shelter near the bottom or in the sediment (McCleave and Kleckner, 1982). Experimental research (Bolliet et al., 2007) supports the idea that the locomotor activity in glass eels might be influenced by environmental and/or social cues such as current, salinity, food availability and density. Recent studies using otoliths microchemistry (Tzeng et al., 1997; Tsukamoto et al., 1998; Tsukamoto and Arai, 2001; Daverat et al., 2005), specifically Sr:Ca ratios in yellow eels, have shown that some individuals do not migrate to freshwater and that catadromy is not an obligate migratory pathway as was previously accepted.

The development of pigmentation provides a useful method of recognizing the different ontogenetic stages in the eel (Table 1.1). In the leptocephalus, the first internal pigmentation develops along the notochord and in the proceeding stages it spreads in a caudo-rostral direction. In English, the unpigmented young are referred to as “glass eels” while the pigmented ones, typically 7–8 cm in length or greater, are called “elvers”. Elvers exhibit a rheotactic response to water flow and this tendency can continue for several years in certain circumstances (Deelder, 1984; Tesch, 2003). The elver stage ends when a length greater than 9 cm and an age of more than 1 year is attained after which they are initially referred to as “bootlace eels” and then yellow eels for eels measuring greater than 30 cm.
When pigmentation is fully complete the eels are referred to as “yellow eels”, although many eels vary in colour from yellow to white on the underside. These eels are at the feeding stage and are primarily sedentary in nature. The usual habit is to feed at night mainly foraging on invertebrates but larger eels regularly eat small fish. Further migrations are only undertaken when weather and water conditions necessitate a change of home territory. It is during this phase that eels undergo most somatic growth and gender differences become evident (Tesch, 2003). The duration of the yellow eel phase is highly variable but generally lasts 5 to 20 years depending on sex (Lecomte-Finiger, 2003).

Following the growth phase, yellow eels undergo a transformation known as “silvering” which marks the onset of puberty and is the beginning of the migratory phase. From then on they are referred to as “silver eels”. Skin colour is generally the most obvious difference between these two stages of the eels’ lifecycle as the silver eels display a silver-white belly and a black dorsal back and darkened fin margins, however, this is subjective and not very reliable method of differentiation (Haro, 2003; Durif et al., 2009a). This colour change is thought to be an adaptation to the pelagic environment as it reduces the conspicuousness of the eel. This silverying occurs concomitant with initiation of puberty, such as the initiation of the gonadotropic axis, but sexual maturation does not proceed beyond the prepubertal (silver) stage so long as oceanic migration is prevented (Dufour et al., 2003).

The transition from yellow to silver eel entails many morphophysiological changes that prepare the fish for the long oceanic migration to the spawning grounds (Durif et al., 2005). There is debate over whether silverying is a secondary metamorphosis (a marked and abrupt developmental change in the form or structure of an animal) (Palstra et al., 2009) or a pubertal event because it has been shown that the morphological changes that occur are induced primarily by the gonadotropic axis (Aroua et al., 2005; Rousseau et al., 2009).
During the transformation significant physiological modifications occur, one of the most important is the beginning of gonad development (Dufour et al., 2003). The eye size increases (Pankhurst, 1982b; Pankhurst and Lythgoe, 1983) and the visual sensitivity of the retina also changes (Archer et al., 1995). The swim bladder structure is altered (Kleckner, 1980; Yamada et al., 2001) so that it is capable of producing up to five times more gas than that of the yellow eel, enabling the eel to tolerate greater the pressure encountered on its oceanic migration. Silver eels also cease feeding and their alimentary tract degenerates (Pankhurst and Sorensen, 1984). This degeneration continues until the completion of their lifecycle but this state is reversible if the eel resumes feeding (Durif et al., 2009b). Changes also occur in the body musculature (Ellerby et al., 2001) and intracellular lipid stores increase (Pankhurst, 1982a). Silver eels absorb water through the alimentary tract and produce more mucus and develop thicker skin in order to maintain osmotic balance (Fontaine et al., 1975). In females the gonad weight increases during silvering, however, the gonadotropic axis is blocked as long as the eel remains in fresh or coastal or water (Durif et al., 2009b). The mean total lengths for male silver eels from different regions lie within relatively narrow limits, namely 35 to 46 cm (Tesch, 2003) but length and age at emigration for female eels are extremely variable and they benefit from attaining a greater size in terms of fecundity (Durif et al., 2009b).

Silvering of eels is largely unpredictable (van Ginneken et al., 2007b) and it occurs at many ages (5–20 years) and sizes (29–101 cm) (Tesch, 2003). Many questions remain on the sequence of events that lead to and trigger the silvering metamorphosis (Durif et al., 2005). Much of the available information on the silvering process has been derived from laboratory studies of hormone-injected eels (Pankhurst, 1982b; Pankhurst and Sorensen, 1984) and no links to the ecology of the fish in its natural environment have been made. The factors that trigger the silvering process are largely unknown as are the different stages that characterise it (van Ginneken et al., 2007a). It has been speculated that a critical amount of fat stores (28%) must be accumulated for eels to silver (Larsson et al., 1990) and Vøllestad and Jonsson (1986) proposed that a minimum size needed to be reached. Durif et al. (2005) concluded that critical fat stores were not a prerequisite
but that silvering was instead triggered by growth related changes in growth hormone. Palstra (2009) hypothesised that early maturation is linked to migration and that swimming itself may be the natural trigger.

Once an eel has undergone silvering it is ready to undertake its seaward migration. Its behaviour changes and it is more receptive to environmental factors that trigger downstream movements. The silver eel migration corresponds with a decrease in temperature (Lowe, 1952) and photoperiod (Vøllestad et al., 1994) and usually starts in the autumn and may continue until early spring (van den Thillart et al., 2009a). Silver eels migrate typically after sunset and during heavy rainfall. It is known that eels are caught in greatest abundance during the last quarter of the moon (Tesch, 2003) and radio-tagged eels have been observed to wait for the darkest conditions to migrate when radiance is low and turbidity is high (Durif et al., 2003). River flow and darkness/turbidity are found to be significant stimuli to the start of migration in most studies (van den Thillart et al., 2009a).

Downstream migrating silver eels meet many obstacles that need to be passed before they reach the sea. Obstacles such as pumping stations, hydropower plants and flood gates are a significant hindrance to migrating eels and can result in mortality or act as a complete barrier to the migration. Svedäng and Wickström (1997) reported on the observations of silver eels regressing to a semi-yellow stage recurrently if they are prevented from immigrating to the ocean and as they regress they resume feeding. In a study carried out on migrating silver eels in the Loire River (Durif et al., 2009b) the author demonstrated that silver eels prevented from migration may regress to yellow eels and then “resilver” the following year.
Table 1.1 Definition of the life stages of the European eel (Moriarty, 1999)

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<th>Name</th>
<th>Definition and habitat</th>
<th>Appearance</th>
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<tr>
<td>Leptocephalus</td>
<td>Larvae, ocean pelagic.</td>
<td>Deep-bodied, strongly compressed, transparent “willow leaf-shaped”.</td>
</tr>
<tr>
<td>Glass eel</td>
<td>Small eel, less than one year post metamorphoses. Continental shelf waters to lower reaches of rivers.</td>
<td>Body form as in adult, largely transparent but with localised pigment.</td>
</tr>
<tr>
<td>Elver</td>
<td>Migrating eel up to 2 years post metamorphosis. Coastal and freshwater. This term is not strictly defined and is frequently used to include glass eel.</td>
<td>Fully pigmented eel, blackish in colour: to length 10 cm.</td>
</tr>
<tr>
<td>Bootlace eel, snig</td>
<td>Small growing, sedentary eel. Coastal and freshwater.</td>
<td>Fully pigmented eel, yellow or brown colour: length 9–25 cm.</td>
</tr>
<tr>
<td>Yellow eel, brown eel</td>
<td>Large growing, sedentary eel. Coastal and freshwater.</td>
<td>Fully pigmented eel yellow or brown in colour: length greater than 20 cm.  Eyes small, body soft.</td>
</tr>
<tr>
<td>Silver eel, bronze eel</td>
<td>Migrating, non-feeding. Freshwater to oceanic.</td>
<td>Silver or bronze colour: length rarely less than 25 cm.  Eyes large, body firm.</td>
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1.2 Decline of the European eel population

The European eel population has been in decline for more than three decades. In recent years the alarming state of the stock has been recognized and it is currently considered to be outside safe biological limits (ICES, 2005)(Figure 1.1). It is listed in the Red Book of Endangered Species, the justification for its inclusion being that the species has undergone a sharp decline in recruitment, yield and stock which will continue into the future (Freyhof and Kottelat, 2008). Juvenile European eel abundance has declined by more than 95\% and the causes of the decline are still unclear, in part because the lack of knowledge of the life history of the eel during its ocean phase (Dekker, 2008). In 2003 Dekker (2003b) concluded from analyses of time series data on eel fisheries in Europe that a major decline in stock and fisheries has occurred since the middle of the 20th century, first evident from the yield of the fisheries of yellow and silver eels and later on the recruitment from the ocean and the yield of the glass eel fishery.

**Figure 1.2** Trended recruitment for the Erne, the Shannon and a mean for 28 stations across Europe (Anon., 2008a)
Numerous hypotheses to explain the decline in recruitment of the eel have been put forward. Factors thought to have a contributory effect include pollution, habitat loss, climatic changes in the ocean, overexploitation for human consumption and eel aquaculture and human caused transfer of parasites and disease (Dekker, 2003b). Castonguay et al. (1994) concluded that no specific hypothesis can be singled out but that the impacts of pollution and habitat modification appear insufficient to explain the decline in recruitment. The effect of climatic changes on the oceanic phase have been speculated on and Castonguay et al. (1994) interpreted the parallel decline in eel recruitment for American and European eel as evidence for a common cause as both species utilise the Atlantic Ocean.

**Pollution**
Eels are particularly sensitive to bioaccumulation and lipophilic contamination and particular concern has been expressed because the level of measured concentrations of some contaminants has been shown to have adverse effects on the quality of the potential spawners. The “quality of spawners” describes “the capacity of silver eels to reach spawning areas and to produce viable offspring” (ICES, 2006). Studies on dioxin-like contaminants such as PCBs in eels have demonstrated that they might affect the quality of spawners by affecting the eel’s ability to complete the migration due to interference with metabolism and hormone status (van Ginneken et al., 2009) and affecting the viability of offspring by impairing normal embryonic development (Palstra et al., 2006). Pollution can also act as a barrier to recruitment into rivers where sewage or industrial effluents are discharged into the river mouth (Moriarty and Reynolds, 1997) and avoidance behaviour of wastewater discharge into streams is well known (Tesch, 2003).

**Habitat loss**
Loss of aquatic habitat in Europe over the last century due to reclamation of coastal and estuarine habitats as well as drainage and dredging etc. is thought to be substantial. These areas constitute suitable eel habitat and though the total area of habitat lost is not accurately quantified it is thought to have a considerable impact on eel stocks. During their lifecycle eels that utilise freshwater habitat for completion of their growing phase
must migrate twice between marine and freshwater habitats. Man-made and natural barriers can, to varying degrees, reduce the accessibility of upstream habitats for young eels arriving from the sea (Feunteun, 2002). Dams, through prevention of upstream migration, have been cited as a major cause of decline in eel abundance in river catchments for both European (White and Knights, 1997a; Feunteun et al., 1998) and American eel species (Verreault et al., 2004). Water resource development such as hydroelectric power plants can have significant effects on the structure and function of a river system (Jackson and Marmulla, 2001) and providing passage for migratory species at dams is critical for maintaining the viability of potadromous, diadromous and catadromous fish populations (Lucas et al., 2001).

Six catchments in Ireland have major hydroelectric power stations in their lower reaches, with 46% of all available wetted habitat upstream of the dams (Anon., 2008a). Other impediments to colonization of suitable habitat by upstream migrant eels include water level regulating weirs, road culverts and abstraction weirs for potable water supplies. The impact of such barriers to upstream eel migration in Ireland has not been quantified (Anon., 2008a) but on a French river system studied by Briand et al. (2005) it was shown that eel population density was more closely correlated with the number of barriers than on distance from the tidal limit.

**Climate change**

The level of eel recruitment to continental waters depends on the reproductive success and the mortality rate of larvae during the marine migration (Feunteun, 2002). The apparent synchrony in the decline of European, American and Japanese eel populations has led researchers to suggest that the oceanic mechanisms relevant to the decline (ocean circulation, temperature and food availability) are similar (Friedland et al., 2007; Kim et al., 2007; Bonhommeau et al., 2008a).

In analysis carried out by Friedland et al. (2007) they found a significant negative correlation between the North Atlantic Oscillation and long-term variations in catches of glass eel stages of the European eel by the fishery independent Den Oever recruitment
index (DOI) in the Netherlands. They proposed that ocean-atmospheric changes in the Sargasso Sea may affect the location of spawning areas by silver eels and the survival of leptocephali during the key period when they are transported towards the Gulf Stream and that these changing ocean conditions could be a contributing factor to declining recruitment of the European eel and probably also of the American eel. The location of the spawning area and the depth of migration appears to have the potential to effect where the larvae may eventually recruit within the species range according to a Langrangian mechanics model applied by Kettle and Haines (2006; Tsukamoto, 2009).

Bonhommeau et al. (2008a) analysed the relationships between the recruitment patterns of European, American, and Japanese eel and patterns of marine primary production in their respective spawning areas and showed survival of eel larvae is strongly correlated with food availability during their early life stages leading them to conclude that the decrease in primary production through climate change processes have therefore affected the recruitment of eel populations.

**Overexploitation**

The European eel has been fished at all of its life stages by commercial and recreational fishermen throughout its distribution area (Dekker, 2008). Since the establishment of national eel management plans by European member states, restrictions on eel fishing, and in the case of Ireland the prohibition of eel fishing, have been put in place. Overfishing of eel stocks has been implicated as a contributory cause for the decline in recruitment (Castonguay et al., 1994; Dekker, 2004) but information to quantify the impact of fisheries on the stock is hardly available (Dekker, 2003b). In Europe there is discontinuity in the data series of landings between countries, incompleteness in coverage, aggregation of data on different life stages and use of different matrices making the data series unsuitable for analysis of trends in landings or for use in making an assessment of the status of the eel stock (ICES, 2009). However attempts have been made to examine the role of eel fishing in the continued decline observed in recruitment. In a model of stock dynamics developed by Åstrom and Dekker (2007) they explored recruitment trajectories under different fishing regimes and their results showed that the length of the recovery period is tightly linked to the level of reduction in fishing or other anthropogenic mortality.
Transfer of parasites and disease

*Anguillicoloides crassus* formerly known as *Anguillocola crassus* (Kuwahara, Niimi and Itagaki, 1974)) is an eel specific parasite. This parasite was originally endemic in East Asia, where it is native, and little intensive research was undertaken because it was thought that they caused few serious health problems to eels (Kirk, 2003). It is a nematode that parasitises the swimbladder of the eel and feeds on blood. It damages the swimbladder wall, an organ important for equalizing pressure, especially in the spawning migration (Tesch, 2003). Experiments performed by Székely et al. (2009) show that swimbladder infection has an adverse effect on swimming performance and increases the stress response in eels and a number of authors have proposed that it is at least partially responsible for the eel’s decline (Sures and Knopf, 2004; Sjöberg et al., 2009). Eels can become infected from the glass eel stage by ingesting infected intermediate hosts such as copepods and prevalence rates as high as 100% have been recorded (Moravec, 1994). *Anguillicoloides crassus* was probably introduced to Europe in the late 1970s or early 1980s through the uncontrolled intercontinental transfer of live eels from East Asia or New Zealand (Peters and Hartmann, 1986; Koie, 1991). The first record of the nonindigenous *Anguillicoloides crassus* in Ireland was from eels captured in the Waterford estuary in 1997 (McCarthy et al., 1999). It has since become well established in several Irish river systems (Morrissey and McCarthy, 2007) and it is estimated that 73% of Ireland’s wetted area is now potentially infected (Anon., 2008a).

A number of viruses are known to cause disease in eels and three of these appear to be widespread in wild populations in western Europe, including; eel virus European (EVE), eel virus European X (EVEX) and Herpesvirus anguillae (HPA). In general these viruses appear to have little impact on infected eels suggesting a certain level of resistance against them (van den Thillart et al., 2009b). However, in laboratory experiments carried out by van Ginneken et al. (2005), where silver eels swam continuously in swim tunnels to simulate the demands of transoceanic migration to the spawning ground, eels infected with the EVEX virus became ill and subsequently died after managing to complete only one quarter of the distance estimated to reach the
spawning grounds. In a separate trial, uninfected eels successfully completed the swimming trial leading the authors to conclude that virus infections may adversely affect eel migration and therefore be a contributory factor to the decline of eel populations.

1.3 National Eel Management Plan

International consideration of the European eel began in 1968 at the 5th session of the European Inland Fisheries Advisory Commission (EIFAC). In 1976 EIFAC, in collaboration with the International Council for the Exploration of the Sea (ICES) held a symposium on eel in Helsinki, establishing the importance of the eel as a target of important commercial fisheries, mostly located within national boundaries but dependent on a spawning stock in international waters. The Helsinki meeting lead to the formation of a working group on eels which has remained in existence ever since and has advanced the sharing of knowledge on the eel and its fisheries. The working group also established a monitoring regime for eel recruitment and has charted the remarkable decline following a peak in abundance in the 1970s (Moriarty and Dekker, 1997). In 1996, because of the continued decline in recruitment and evidence of the rapid spread of the swimbladder parasite Anguillicoloides crassus, attention was focused on the need to protect eel stocks. In 1998 the ICES Advisory Committee on Fisheries Management concluded that the European eel stock was at a historically low level, outside safe biological limits, and suffering a massive anthropogenic impact and it gave the precautionary advice that a protection plan and emergency measures were required urgently. Following this pronouncement members of the ICES working group identified potential causes of the downward trends in recruitment and stock, proposed precautionary management targets and suggested mitigation measures in relation to conservation objectives (Dekker et al., 2007). It was not until 2003, however, that the European Commission proposed a Community Action Plan for the protection of the eel, built up from a set of local actions to be put in place by member states according to an agreed standard (CEC, 2003). This was the first time that the management of a catadromous species, the European eel, was addressed at a European level (Penas, 2007).
In 2007 the European Commission published Council Regulation (EC) 1100/2007, establishing measures for the recovery of the eel stock (EC, 2007). This regulation mandated the implementation of an eel management plan in all member states that contain natural habitat of the European eel. The regulation also stated that eel management plans should be prepared for all river basins, including transboundary basins, as defined in accordance with the Water Framework Directive (EC, 2000) in order to ensure coordination and consistency between the regulation and previous directives on conservation and enhancement of aquatic environments. In order to evaluate the effect of the management action undertaken each member state is required to report to the Commission initially every third year, with the first report to be presented by 2012.

The objective of each eel management plan is to reduce anthropogenic mortalities in order to achieve with high probability the target escapement to the sea of at least 40% of the silver eel biomass relative to the best estimate of the escapement that would have existed if no anthropogenic influences had impacted the stock.

Ireland has prepared a National Report for Ireland on the Eel Stock Recovery Plan (Anon., 2008a) and it covers five River Basin District Eel Management Plans and one transboundary Eel Management Plan. Four main management actions aimed at reducing eel mortality and increasing escapement were proposed in the report and include cessation of the commercial eel fishery, mitigation of the impact of hydropower, including a comprehensive silver eel trap and transport plan, ensure upstream migration of juvenile eel at barriers and improve water quality including fish health and biosecurity issues.

In relation to the management target of ensuring upstream migration of juvenile eels at barriers the plan aims to evaluate the extent to which existing barriers impede upstream
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migration of eels and to consider management measures that will improve accessibility and negate any current impact. It states that all new installations proposed on rivers are to include an evaluation of all direct and indirect impacts on eels and that measures are to be undertaken so as to minimise these impacts. It also proposes to continue with the operation of assisted migration of juvenile eels at hydroelectric facilities on the Shannon and Erne river systems through the use of eel ladders and “in the event of recovering recruitment, a stocking strategy will be developed by stocking "surplus" recruits into good quality (e.g. low contaminants, no Anguillilcoloides crassus) catchments where stocks are identified to be low” in accordance with the stocking strategy drafted by the ICES working group on eel (ICES, 2006).

Through implementation of the management actions the National Report states there will be no fishing mortality and markedly lower turbine mortality and that according to model of stock dynamics developed by Astrom and Dekker (2007) this should result in recovery of recruitment within approximately 90 years and achievement of the EU escapement biomass target in a similar or shorter timeframe, assuming the average European anthropogenic mortality is reduced to a comparable level.

1.4 The eel in Ireland
The European eel is one of a few species of indigenous and widespread fish in Ireland. Ireland has a less diverse fish fauna when compared to continental Europe because as an island only fish with marine affinities were able to colonise the country after the last Ice Age (Maitland, 2004). The eel has been fished in Ireland since Mesolithic times some 9000 years ago. In the 1970s the archeologist Peter Woodman found evidence of eel and other fish during the excavation of Ireland’s earliest human settlement at Mount Sandel in county Derry (Woodman, 1985; Woodman and Mitchell, 1993). In 1977 during an excavation of another Mesolithic site on the shores of Lough Boora in county Offaly the burnt bones of eels were found at a number of hearths (Ryan, 1980). References to eel fishing in Ireland are frequent in historical manuscripts, for example in
a paper on eel fishing in Athlone by Went (1950) there are references of a receipt for the sale of eels recorded in the year 1293. The first Ordnance Survey maps of Ireland published in 1837 have a large number of “eel weirs” identified on them (Moriarty, 2003).

Early scientific references to the eel in Ireland appeared at the beginning of the last century (Schmidt, 1906; Holt, 1908). In the seminal paper titled “The breeding places of the eel” Schmidt (1923) referred to the collection of eel larvae from the west coast of Ireland made by GP Farran in 1904 while onboard the SS “Helga”. This sample, along with Schmidt’s own sample from the west of the Faroe Islands collected in the same year, was among the first gathered outside the Mediterranean. Sightings of eel “fry” in the tidal and freshwater sections of Irish rivers were recorded in reports compiled by Holt (1908) and Hillas (1911) for the Department of Agriculture and Technical Instruction of Ireland. The distribution of historic eel weirs in Ireland was recorded by AEJ Went who also published extensively on the history of fisheries and fishing methods in Ireland including papers on the Galway and Athlone eel weirs (Went, 1943; 1950).

A study of eels in Irish lakes was commissioned by the Department of Agriculture and Fisheries in 1967, with the primary objective of ascertaining why eel production was exceptionally low in contrast to Lough Neagh in Northern Ireland and a number of lakes from continental countries at similar latitudes (Moriarty, 1972). Fishing was carried out using fyke nets and data was collected on eel size, sex and diet. Moriarty arrived at the conclusion that the low yield attained in the Republic of Ireland resulted from topographical features of the river systems and from disruption of elver ascent by hydroelectric dams (Moriarty, 1984). However, by the late 1980s Moriarty had revised his conclusion in regard to the Shannon River system stating that the stock had increased due to a very effective enhancement operation and that fishing effort was too small to exploit the stock adequately (Moriarty, 1988). In 1996 Moriarty gave an account of
variations in the numbers of yellow eel caught by constant effort using fyke nets in a small bay on Lough Derg on the Shannon River system over a period of 14 years, from 1981 to 1994. He noted that there was a very poor catch in August 1994 and suggested this was either a chance variation or could have been a first indication of the effects of poor recruitment or of increased commercial fishing effort (Moriarty, 1996).

The collection of detailed records of quantities of young eels ascending elver ladders at the Parteen regulating weir on the River Shannon was initiated in 1977 and provided data on the juvenile eel migration with reference to length, weight and age of samples (Moriarty, 1986). Moriarty also summarised the catches of the silver eel fishery on the Lower Shannon for the period from 1964 to 1988 and contributed records to international reviews of eel fisheries in Europe (Moriarty, 1990; Moriarty and Dekker, 1997).

In the early 1990s it was recognised that the shortage of elvers being stocked or recruited naturally to the major eel fisheries was a serious limitation to development of the Irish eel industry. Forbairt, the government agency charged with the development of indigenous industry in Ireland, commissioned a report to investigate the extent of the problems and the manner by which they could be overcome. The report written by McCarthy et al. (1994c) reviewed status of commercial eel fishing in Ireland and data on the quantity of eels recruited to a number of Irish river systems was reviewed. The options for enhancement of the Irish eel stock were considered and some key recommendations were that yields from glass eel fisheries for the purpose of stocking be optimized and to closely monitor future developments in eel fisheries, in particular the relative contributions of stocked elvers and fingerlings to yields.

The decline in the number of elvers trapped on the Shannon River system in the 1980s prompted research into eel recruitment in the estuary and lower reaches of the Shannon
(Reynolds et al., 1994) as part of the 1992–1994 Shannon Eel Management Programme funded by ESB, Fishery Conservation. Under this programme improvements of elver trapping facilities and the possibility of establishing a glass eel fishery to complement elver stocking were investigated. Walsh (1996; Walsh and Reynolds, 2009) also studied the parasitology of glass eels in the Shannon estuary. Later an intensive study of the potential of harvesting glass eels in the Shannon estuary for the lake stocking programme was undertaken from 1995–1999 and involved the establishment of a pilot scale glass eel fishery which contributed significant numbers of eels in those years (O'Connor, 2003; McCarthy et al., 2008a). In parallel to the work of Reynolds et al. (1994) under the Shannon Eel Management Programme, McCarthy et al. (1994a) evaluated the prospect of developing a fyke net fishery for yellow eels in the Shannon lakes and investigated the status and potential of the silver eel fishery (Cullen, 1994; McCarthy et al., 1994b). Purcell (1994) studied the parasites of eels in the Shannon system with particular reference to the eels of Lough Derg and later Naughton (2001) carried out studies on the parasitology of eels from a number of catchments across Ireland including the Waterford estuary where the first record of Anguillicoloides crassus in Ireland was made (McCarthy et al., 1999). This swimbladder nematode spread rapidly to the principal exploited eel fisheries including the Shannon (McCarthy et al., 2009).

Copley (1999) studied the ecology of eels in the River Erne system. Her work included studies on the parasitology of eels and she recorded the presence of the gill parasite Pseudoactylus bini (Kikuchi 1929) in Ireland for the first time (Copley and McCarthy, 2001). She also analysed the stocking programme records for the River Erne and found that recruitment patterns varied between and within years and concluded that the relationship of daily or annual catch levels to environmental factors was generally complex and not attributable to a single environmental parameter.
The River Erne eel enhancement programme (Matthews et al., 2001) was initiated in 1997. It was a cross border programme involving a number of agencies and its main objective was to develop a management strategy to realize the full potential of the Erne eel fishery. One of the primary aims of the programme was to maximize recruitment of glass eel and elver to the Erne system and experimental glass eel fishing using Tela nets was undertaken in 1998. The stocking policy was also altered so that glass eels and elvers were distributed to all parts of the catchment. Fyke net fishing surveys were undertaken to assess the status of the yellow eel stocks and to obtain samples for investigating the age, growth, diet and parasitology of the eels. Evans et al. (2001) documented the spread of the swimbladder parasite Anguillicoloides crassus through the Erne system as part of the research programme.

Relatively little scientific research has been completed on the eel population of the River Lee catchment. In a report “Strategy for the development of the eel fishery in Ireland” Moriarty (1999) mentions that a fyke net fishery operated successfully in Lough Allua for some years. He also indicated that there was potential for the development of a yellow eel fishery in the Lee reservoirs but cautioned that the fishing effort should be restricted to one crew until stocking increased the population. With regard to eel recruitment he noted that in spite of the Lee’s large catchment and extensive estuary “the persistent failure of efforts to establish fyke net fisheries in the tidal waters suggests the supply of elvers is limited” (Moriarty, 1999). In preparation for the National Eel Management Plan a survey of the river and reservoir eel population of the Lee catchment was undertaken in 2006 (McCarthy et al., 2008b). As part of the survey fyke net fishing was undertaken on the two reservoirs on the River Lee where CPUE values were found to be higher than anticipated and there were a high percentage of large female eels captured.

The Lough Neagh eel fishery is the largest remaining commercial source of wild European eels, producing 16% of total EU landings in 2007 (ICES, 2010) and it has
received much attention from fishery scientists and commercial interests over the years. Its commercial importance in the past can be seen from the many legal disputes over ownership of the resource that took place in the 19th century (Woodman and Mitchell, 1993). Early scientific studies of the fishery were made by visiting consultants in the 1930s but no systematic research was undertaken until 1965 (Moriarty, 2003). The elver migration on the River Bann leading to the Lough Neagh eel fishery was studied in the 1930s (Menzies, 1936) and later Lowe (1951) investigated the factors influencing migration of elvers on the river. Frost (1950) published a description of the silver eel fishery of Lough Neagh as well as observations on the age of silver eels following research undertaken in the mid-1940s. A detailed examination of the eels in Lough Neagh was undertaken by Parsons et al. (1977) when they studied the relationship between elver recruitment and changes in growth and sex ratios of silver eels and found that there was a significant increase in the proportion of male silver eels captured following periods of upstream elver transport to the lake which took place from 1932 to 1947 and from the 1960s onwards.

In 1971 the Lough Neagh Fishermen’s Co-operative took full ownership of the fishery which allowed the co-operative to pursue the aim of achieving maximum sustainability of employment for fishers while preserving the fishery for future generations. A yellow and silver eel fishery is controlled through a combination of measures implemented through state law in conjunction with restrictions imposed by the co-operative. A key policy of the co-op, which has been ongoing since 1984, is the purchase of glass eels from European markets for stocking Lough Neagh (Rosell et al., 2005). In 2006 an assessment of the impact of this additional stocking was carried out using a predictive model of the yellow and silver eel fishery output based on the natural and stocked glass eel input, fishing effort and environmental variables (Allen et al., 2006). The authors concluded that additional glass eel input was not a significant predictor for yellow or silver eel output.
Immigration of glass eel and elver to the Corrib River system has been studied by McGovern and McCarthy (1992a). A number of papers on the parasitology of eels from the Corrib have also been published (Conneely and McCarthy, 1984; Conneely and McCarthy, 1986; McCarthy and Rita, 1991). McGovern and McCarthy (1992b) used acoustic telemetry to track movements of yellow eels in the River Clare which flows into Lough Corrib. The study demonstrated the ability of yellow eels to return to specific loci and establish variable activity areas during different periods of the diel cycle and under varying weather conditions.

The Burrishoole catchment in the west of Ireland is an oligotrophic system of rivers and lakes where its unexploited eel population has been studied since the 1950s, facilitated by the use of upstream and downstream fish traps. Poole et al. (1990) examined the data set on silver eel migration, including daily counts, size variations and sex ratios. They found that there was a decline in numbers of eels migrating but the total weight of eels was not affected. They also observed a change in sex ratio from 94.5% males in 1962 to 37.5% in 1988. The most recently reported silver eel sex ratio for catchment is 29% male for the period 2003-2008 (ICES, 2010). The age and growth rates of juvenile eel (Poole et al., 2004), yellow eel (Poole and Reynolds, 1996a) and silver eel (Poole and Reynolds, 1996b) have been investigated from samples collected in the catchment.

Santillo et al. (2005) analysed levels of brominated flame retardants and polychlorinated biphenyls from eels captured in Lough Furnace and the Owengarve River in county Mayo as part of a wider investigation of contaminants present in eels sampled from 10 European countries. Their results showed that the samples from Ireland contained low levels of all contaminants measured. McHugh et al. (2010) published the results of a study on the occurrence of persistent chlorinated and brominated organic contaminants and the lipid levels of eels from five Irish river catchments. They found that with the exception of one sample from the Burrishoole catchment in county Mayo, the levels of persistent organic pollutants (POPs) were low compared to those in other countries.
However, they highlighted that potential for factors such as localised contamination or the accumulation of POPs in reproductive organs needs to be considered when evaluating the potential for health effects in eels.

Irish fisheries scientists contributed to the Study Leading to the Informed Management of Eels (SLIME) project which was funded by the EC commission in 2006. The project focused on development of stock dynamics models with the aim to develop quantitative approaches to evaluate the status of national eel stocks at a river basin level in order to provide scientific advice for the development of eel management plans (Dekker et al., 2006). Case studies from the Lough Neagh eel fishery (Rosell, 2006), the Burrishoole (Poole and de Eyto, 2006) and the Shannon (McCarthy and Blaszkowski, 2006) river systems were provided with details of past commercial catches, records of stocking programmes and results of scientific surveys of the eel populations. Ireland is also one of seven European countries represented in the EELIAD project (www.eeliad.com), which is investigating the ecology and biology of European eels during their marine migrations. One of the main objectives of the research is to determine the migration routes and behaviour of female silver eels during their spawning migration through the use of pop-up satellite archival transmitters (ICES, 2010).
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1.5 Aims

This study was initiated in order to improve the understanding of the biology and behaviour of juvenile eels migrating upstream in the Shanon, Erne and Lee river systems. Particular attention was given to investigating the issues relating to juvenile eels posed by the presence of hydroelectric power stations and related structures.

The specific aims of this study fall under two headings, namely, studies on juvenile eel biology and studies on the provision of upstream passage for migrating eels.

Juvenile eel biology

- Establish the abundance, seasonal duration and variation in timing of eel recruitment to the Shanon, Erne and Lee river systems and examine the biological characteristics of migrating juvenile eels including length, weight and age.
- Investigate the effect that environmental and meteorological factors may have on the migration dynamics of juvenile eels of *Anguilla anguilla* in the River Shannon system at the Parteen regulating weir.
- Examine juvenile eels from the Shannon, Erne and Lee systems for the presence of *Anguillicoloides crassus* and determine its prevalence and intensity of infection in the eels sampled.
- Investigate possible relationships between eel length and condition and the infection intensity of *Anguillicoloides crassus*.
- Examine variations in the size structure and development of pigmentation of glass eels and elvers sampled at a number of estuarine sites along the west coast of Ireland and investigate the population structure and density of potential juvenile eel migrants in riverine habitat downstream hydroelectric facilities.
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Provision of upstream passage for migrating eels

- Examine juvenile eel trapping techniques currently in use at hydropower facilities and improve juvenile eel traps in order to reduce their size selectivity.
- Assess the efficiency of the juvenile eel trap at the Parteen regulating weir on the River Shannon through mark and recapture experiments and identify additional sites for the trapping of juvenile eels on the River Shannon at the Parteen regulating weir.
- Establish the extent to which juvenile eels use alternative routes of migration upstream at hydropower facilities by employing trapping methods and closed-circuit video cameras.
Chapter 2  Study Area

2.1 The River Shannon and its catchment

The River Shannon (Figure 2.1) is the longest river in Ireland and the British Isles. Its source is the “Shannon Pot” a karst rising on the slopes of the Cuilcagh Mountains in counties Cavan and Fermanagh (Delaney, 2000). Its freshwater reach extends southwards 251 km from the Cavan-Fermanagh border to Limerick city. Its estuary is a further 83 km long passing between the counties of Clare and Kerry. Its total catchment area including its estuary is 14,100 km$^2$ and occupies 17% of the land area of Ireland draining 12 counties in whole or in part. In the 205 km of its length between Lough Allen and Killaloe there is a fall of just 17 m and the river is consequently characterised by slow flowing lacustrine expanses bordered by callows, bogs and wetlands, frequently breaking its banks in times of flood. In the remaining 25 km of its freshwater reach it drops by a further 30 m. The flow in the River Shannon has been controlled for over 200 years to aid navigation and in the 1920s the river was harnessed for hydro electricity generation which resulted in much of the flow in the reach downstream of Lough Derg being diverted to the generating station at Ardnacrusha (Figure 2.1)(Bowman, 1998).

The River Shannon has been an important trading route for over 1000 years and many early Christian settlements were established along its banks, the most well known being Clonmacnoise. Founded by St. Ciaran around AD 545, Clonmacnoise was at the very crossroads of Ireland, where the Shannon was crossed by “the great road” along the Eiscir Riada, Ireland’s most important east-west thoroughfare in early historic times (Harbison, 2000). The river has been navigable from Killaloe northwards to Carrick-on-Shannon since the end of the 18th century but the limited commercial traffic of the late 19th and early 20th centuries ceased in the 1960s (Bowman, 1998).
Many lakes occur along the main channel and on the tributaries and they are particularly noted for their amenity value. Recreational uses include pleasure cruising and game and coarse angling. The lakes are also important abstraction sources for potable water.

Agriculture is the main economic activity in the catchment and over 70% of the land area is farmed. Livestock grazing on pasture is the most widespread type of farming and milk and meat processing are the most prominent industries in the catchment. Forestry and peat harvesting are also important economic activities. Peat has been used since the 1940s to fuel the generation of electricity in local power stations and more recently to supply peat moss to the horticulture market (Anon., 2010b). Light mechanical engineering, electrical engineering and pharmaceutical industries are located in the towns.

Most of the catchment is underlain by carboniferous limestone overlaid by varying thickness of glacial drift deposited during the Ice Age. Small areas of higher ground formed from younger shale and sandstone rocks on top of the limestone, such as the hills surrounding Lough Allen. Any other diversity in the landscape is the legacy of the last glaciations and includes the drumlins of South Leitrim, the moraines and eskers in the central Shannon area, the topography suitable for later bog formation, the major lakes, Lough Ree and Lough Derg (Weaving and Levinge, 2000).

Moderate ionic content and relatively soft waters characterise the headwater reaches of the Shannon. As the river progresses into the more soluble limestone plain the ionic content increases, thereafter the influence of the main tributaries is marked as their relatively high conductivity waters lead to increases in ionic content of the Shannon. There is substantial variation in pH level in the headwater streams, most of which range from acid to slightly alkaline. On leaving Lough Allen the pH of the water is circum
neutral but due to strong alkaline influents the water becomes increasingly alkaline further downstream (Bowman, 1998).

Water quality in Ireland is monitored by the EPA and a range of agencies based on criteria and standards set out in the Water Framework Directive (WFD) (EC, 2000). A variety of parameters are monitored to identify the “ecological status” of a waterbody defined in the WFD as an; “expression of the quality and functioning of aquatic ecosystems based on biological quality elements and supporting hydromorphological and physico-chemical elements”. Planning, management and reporting for the WFD is based upon River Basin Districts and these are based upon large river basins or a combination of smaller neighbouring basins and include all rivers, lakes, estuaries, coastal waters and associated groundwaters.

The Shannon International River Basin District (Sh-IRBD) (Figure 2.4) includes the natural drainage of the River Shannon as well as coastal parts of counties Clare and Kerry which drain to the sea. It is defined as an international river basin district because a small portion of county Fermanagh in Northern Ireland drains underground to the source of the Shannon where it rises to the surface in county Cavan (Anon., 2010b). A nine percent decline in the percentage of unpolluted channel length was noted in the Sh-IRBD for the period 2007–2009 with a corresponding increase of slight pollution. An overall increase in the percentage of channel length classified as seriously polluted was also noted. 22 (43%) lakes representing 88% of the 368 km² monitored lake area were assigned high or good physico-chemical status. Moderate physico-chemical status was assigned to 29 lakes (57%) representing 12% of lake area in the district. High or good biological status was assigned to 23 of the lakes in the Sh-IRBD, representing 62 km² of lake area monitored. There were 28 lakes at moderate biological status representing 306 km² of the monitored lake area in the RBD.

The ecological status, based on the water framework directive definition, ascribed to Lough Derg, the largest lake on the River Shannon was poor (Anon., 2011). Lough
Derg had been classified as strongly eutrophic in the early 1990s but since 1997 it has been reclassified as mesotrophic. This change is due in a large measure to the reduction in planktonic algal growth in the lake which may be attributable to the impact of the non indigenous zebra mussel infestation. The zebra mussel, *Dreissena polymorha*, was first recorded in Lough Derg in 1997 (McCarthy *et al.*, 1997) and is sustained by filtering particulate matter including planktonic algae from the surrounding water. This has the effect of reducing the concentration of such materials in the water and in this manner phosphorus concentration in the lake water is also reduced, as that fraction of the element that is contained in the algae and other suspended material is removed through the filtering process and is transferred to the sediment as faecal matter. In this process the zebra mussel has an important influence on the concentration of the nutrient causing eutrophication and also on the parameters chlorophyll and water transparency which are used to measure the extent of eutrophication in lakes (Clabby *et al.*, 2008).

Monitoring of fish status was undertaken by the Central Fisheries Board at 44 sites in the Shannon River Basin District between 2008 and 2009. The reference condition applied for the Water Framework Directive for Irish rivers is that rivers should have viable populations of salmonid fish such as trout and salmon. Generally sites even at moderate status may still have some salmonids but with unbalanced populations. At poor and bad status salmonids are generally absent. 49% of sites surveyed were of good or high status, 44% were moderate and 7% poor or bad (Anon., 2011).

The River Shannon was harnessed for electricity generation following the construction of the Ardnacrusha generating station (86 MW) between 1925 and 1929. The hydroelectric facilities on the Shannon include a weir at Parteen that diverts most of the water via a canal to the Ardnacrusha hydroelectric power station (HPS) located at the head of the estuary. A statutory compensatory flow of water of 10 m$^3$s$^{-1}$ is discharged to the main river channel which meets the tailrace of the Ardnacrusha HPS approximately 15 km downriver. Flood water is allowed to pass down the original river.
channel by opening sluice gates at the Parteen regulating weir if necessary. The average annual discharge through the system is $108 \, \text{m}^3 \, \text{s}^{-1}$ but can go up to $750 \, \text{m}^3 \, \text{s}^{-1}$ in a winter flood (between station discharge and spillage at the Parteen regulating weir).

Elver traps, which also capture small ascending “bootlace” eels, have been operated at Ardnacrusha since 1959 and a trap located at the Parteen pool and traverse type fish pass is also in use since 1985 to trap ascending small yellow eels (McCarthy et al., 2008a).
Figure 2.1 Map of the Shannon catchment, showing the locations of Ardnacrusha HPS and the Parteen regulating weir as well as major lakes and river sub-catchments
2.2 Lough Erne and its catchment

The Erne catchment which makes up part of the North Western International River Basin District (NW-IRBD) (Figure 2.4) spans the border between Northern Ireland and the Republic of Ireland covering an area of 5,275 km\(^2\) and encompassing a large and intricate lake system (Figure 2.2). The upper catchment is located in the Republic of Ireland in the counties Monaghan, Cavan and Leitrim. The lower catchment is located in Northern Ireland and its two major lakes are Upper and Lower Lough Erne which are situated in county Fermanagh. The Erne drains in a north-westerly direction through Loughs Gowna, Oughter, Upper Lough Erne and Lower Lough Erne before entering the sea at Ballyshannon, county Donegal in the Republic of Ireland (Anon., 2008b). There are numerous small lakes connected directly or indirectly to the upper catchment and they have a diverse water chemistry reflecting the varying underlying geology.

The River Erne has two hydroelectric power stations on its lower reaches, which were commissioned in the early 1950s. Cathaleen’s Fall HPS (45 MW) is located at the tidal limit on the river in Ballyshannon, county Donegal and has a head height of 27 m. A second and smaller (18 m head, 20 MW) HPS is situated at Cliff, just below Belleek, county Fermanagh. The average annual discharge through the Erne system is 92 m\(^3\) s\(^{-1}\).

The upper and lower lake basins of the Erne catchment are underlain predominantly by Carboniferous limestone and there are some notable marl lakes in the Finn and Lackey sub-catchments. There are some important areas of Devonian and Carboniferous sandstone and the water chemistry of the lakes reflects the mixture of carbonate-rich water from the limestones and soft acid water from the sandstones (Gibson, 1998).

Intensive livestock farming in the Cavan-Monaghan area has resulted in eutrophication of many of the lakes in the upper Erne catchment, with Loughs Oughter, Sillan and White lake classified as hypertrophic or seriously polluted due to agricultural
enrichment. The intensification of agriculture within the system led to high increases of the volumes of wastes that required disposal, usually by land spreading. In the 1970s and 1980s, significant fish kills were common due, in the main, to poor farming practice causing both point source and diffuse pollution (Anon., 2008b).

In the past the Erne catchment had adequate water quality and suitable habitat for self sustaining populations of Atlantic salmon (Salmo salar L.) and brown trout (Salmo trutta L.). However, the deterioration in water quality assisted a collapse of the migratory salmon and now only small sub-catchments can sustain indigenous brown trout. The introduction of the zebra mussel to the Erne in 1996 (Rosell et al., 1998) and its spread throughout the system has provided a further impact resulting in dramatic reductions on phytoplankton abundance and increased water clarity in parts of the system (Anon., 2008b).

In Northern Ireland, river basin management plans drawn up to comply with the Water Framework Directive are implemented through Local Management Areas (LMA) by the Northern Ireland Environment Agency. When assessing water quality both ecological and chemical quality as well as the pressures that can affect these factors are considered. 76% of the surface water bodies in Upper Lough Erne LMA have been classified as less than good and the main reason is inadequate levels of dissolved oxygen (Anon., 2009c). In the Lower Lough Erne LMA, 73% of the surface water bodies have been classified as less than good and the main reason was the negative impact on the invertebrate communities (Anon., 2009b).

In the Erne catchment the high rainfall and poor ground drainage limit the agricultural land use to livestock rearing including pigs, sheep, cattle and poultry. The sub-catchments vary greatly in agricultural intensity in response to altitude and soil type.
All of the major industries in the area are linked to agriculture or tourism although forestry is an important land use in the upland areas (Gibson, 1998).

Provision for the upstream movement of eels was included in the construction of the hydroelectric power stations (HPS) with elver passes located at both Cathaleen’s Fall and Cliff. Records of elver catches have been taken at Cathaleen’s Fall since the 1960s when partial trapping was carried out while an unknown number of juvenile eels ascended to the upper catchment using eel ladders at each of the dams. In the 1960s the original eel ladder at Cathaleen’s Fall was decommissioned as it was considered that the climb to be undertaken by the ascending eels was too arduous and resulted in significant mortalities. From 1970 onwards total trapping was carried out at two eel traps at Cathaleen’s Fall providing a long term dataset for recruitment to the Erne. In 1994 a third trap was installed. An undocumented number of juvenile eels have also been reported to use the fish pass at Cathaleen’s Fall as a means of upstream passage during the summer months (Anon., 2006).
Figure 2.2 Map of the Erne catchment, showing the locations of hydroelectric power stations (HPS), major lakes and river sub-catchments
Chapter 2

2.3 The River Lee and its catchment

The River Lee is one of the largest rivers in south-west Ireland with a catchment area of 1,254 km$^2$ (Figure 2.3). It is included in the South Western River Basin District (SW-RBD) (Figure 2.4). The Lee rises 606 m above sea level at Goughganbarra in the Shehy Mountains and flows eastwards in a structurally guided valley past Cork City to the mouth of Cork Harbour where it empties into the Celtic Sea. Its main tributaries include the Sullane, Laney, Dripsey, Martin, Bride and the Shournagh. There are three impoundments along the main channel namely Lough Allua, Carrigadrohid Reservoir and Inniscarra Reservoir.

The River Lee was harnessed for electricity generation between 1953 and 1957 when the Carrigadrohid (8 MW) and Inniscarra (19 MW) generating stations were commissioned. The scheme involved the creation of reservoirs upstream of both stations. 27% of the catchment is located downstream of the Inniscarra reservoir and the tidal limit of the river is 14.5 km downstream of the Inniscarra station (O'Halloran, 1998).

Figure 2.3 Map of the Lee catchment showing the locations hydropower stations (HPS), major reservoirs, lakes and river sub-catchments
In the headwaters of the Lee the geology is Carboniferous Lower Avonian shales, sandstones and slates. The Geragh, an area of mixed deciduous alluvial woodland in the floodplain of the River Lee and most of the rest of the catchment is underlain by Old Red Sandstone. The soils of the upper catchment are predominantly peaty podzols and blanket peats in the sandstone and shale. Poorly drained brown earths overlie the glacial deposits (O'Halloran, 1998).

The Carrigadrohid and Inniscarra reservoirs are classified under the Water Framework Directive as “heavily modified waters”. Both of these reservoirs are identified as currently not reaching their equivalent potential standard (Anon., 2011). The Lee catchment has been classified as being of poor biological status for fish; however, it was noted that confidence in classification of this “newer” biological indicator is low (Lucey, 2009).

In 2005 the EPA reported that the significant improvement in the trophic status of Carrigadrohid Reservoir compared to conditions recorded in the early 1990s was maintained during the period of monitoring. Carrigadrohid was classified as mesotrophic for this period and increased phytoplankton growth was noted. In 2003 serious pollution was recorded in the River Bride, a tributary of the River Lee and municipal waste was suspected as the cause. The Lee Estuary was described as being in an “impacted condition” due mainly to the severe levels of deoxygenation consistently observed at sampling sites (Toner et al., 2005).

In the River Lee EPA monitoring data indicates that water quality is generally satisfactory apart from sites such as Inniscarra Bridge where it was classed as highly eutrophic in 2001 and of poor ecological status in 2008. In 2005 a major disruption to fauna at a sampling site upstream of Goughganbarra Lake was reported where salmonid parr and other age classes were killed due to concreting work carried out on a bridge upstream of the site (Anon., 2010a).
The River Lee catchment upstream of Cork city is largely a rural watershed. In the upper catchment rough pasture and moorland predominate with significant areas of certain sub-catchments covered by forestry plantations. In the Martin and Dripsey catchments and the area surrounding the Carrigadrohid and Inniscarra reservoirs, much of the land is of good quality and intensive dairy and pig farming is carried out. There are no large industries giving rise to liquid effluent within the catchment upstream of Cork city (O'Halloran, 1998).

The Inniscarra and the Carrigadrohid reservoir as well as the natural lakes of the upper parts of the river system (e.g. Lough Allua) are known to be inhabited by eel populations. Eels are also widespread in the lower parts of the river basin, with 27% of the catchment area being below the Inniscarra dam and in parts of Cork Harbour to which the River Lee discharges 14.5 km downstream. Periodic ascent by juvenile eels to the reservoirs must have occurred via the Borland lift (McCarthy et al., 2008b) as no eel specific fish passage or trap and transfer facilities were incorporated in the construction of the dams. In 2008 an elver pass trap was installed below the Inniscarra HPS to enhance the level of juvenile eel migration to the upper catchment.
Figure 2.4 Map of Ireland showing the approximate locations of hydroelectric facilities within the three Water Framework Directive River Basin Districts where this study was undertaken
Chapter 3  Juvenile eel abundance, migration timing and biological characteristics of juvenile eels in riverine areas

3.1 Introduction

Monitoring of recruitment by assessing glass eel fishery yields and catches of juvenile eels in eel ladders has been used as a tool to determine eel stocks at a local and European scale for over 30 years (Feunteun, 2002; ICES, 2010).

On rivers harnessed for hydroelectricity generation juvenile eels encounter dams and weirs as they progress upriver. Trapping of juvenile eels when they arrive at these obstacles has been used as a means of monitoring recruitment levels and for stock enhancement through distribution of juvenile eels to suitable habitats upstream in Europe, (Moriarty, 1986; Vøllestad and Jonsson, 1988; McCarthy et al., 1999), North America, (Jessop, 2003a; McGrath et al., 2003; Dutil et al., 2009) and New Zealand (Jellyman and Ryan, 1983; Boubée et al., 2008). Trapping presents an opportunity to better understand the factors that affect recruitment such as environmental conditions (Jessop, 2003b; Acou et al., 2009) and it also gives an opportunity to obtain information on the biology of upriver migrating eels (Solomon and Beach, 2004).

The European eel population has been in decline for more than three decades and it is currently considered to be “outside safe biological limits” (ICES, 2010). In 2008 the European eel was included in the International Union for the Conservation of Nature and Natural Resources (IUCN) Red List of threatened species under the category “critically endangered” (Freyhof and Kottelat, 2008). Recruitment to the eel stock is at a historically low level and all of the glass eel and elver recruitment-series for Europe show a clear decadal decline since the early 1980s (ICES, 2010). In 2009 it was estimated that recruitment of glass eels to the continental North Sea and the continental Atlantic areas of Europe was < 1% and 9% of pre 1979 levels respectively (ICES, 2009).
This trend in recruitment for the European eel is derived from long term series collected in estuaries from various locations around Europe. These data series are considered the most appropriate indicator of the status of the eel stock as there is no pan-European evaluation of silver eel escapement (ICES, 2010). The severity of the decline in eel recruitment that has occurred in the rest of Europe has also been observed in Ireland. At Ardnacrusha on the River Shannon and Cathaleen’s Fall on the River Erne monitoring of elvers migrating upstream is carried out using fixed elver traps and annual catches at both locations have declined dramatically in the past three decades. At Ardnacrusha catches declined from 4500 kg in 1980 to 49.73 kg in 2010, and at Cathaleen’s Fall the corresponding catches declined from 1300 kg to 93.86 kg.

Upstream migrating juvenile eels have been trapped in the lower River Shannon for the purpose of stocking of lake and upstream river sites since 1959 (McCarthy et al., 1999), however, records for Ardnacrusha and Parteen in terms of numbers and weights of juvenile eels trapped are only available since 1977. During the period from the mid 1960s to the mid 1980s significant catches of elvers were made at estuarine tributaries of the River Shannon, in particular at the River Feale and the River Maigue and these elvers were used to supplement catches from Ardnacrusha and Parteen (McCarthy et al., 1994c). The stocking programmes were most productive from the late 1970s to the early 1980s when catches of elvers were at their highest at Ardnacrusha and the estuarine tributaries. In 1979 for example, over 10,000 kg of elvers were captured (McCarthy et al., 2008a). The quantity of juvenile eels stocked to the River Shannon declined progressively after the mid 1980s, due in part to the Europe-wide decline in eel recruitment. A dramatic decrease in annual catches of elvers at Ardnacrusha was noted and catches of elver and bootlace eels at Parteen also decreased but not so markedly (McCarthy et al., 1999).

On the River Erne, records of elver catches have been taken at the Cathaleen’s Fall dam since the 1960s when partial trapping was carried out, while an unknown number of
juvenile eels ascended to the upper catchment using eel ladders at each of the two dams on the river system. In the 1960s the original eel ladder at Cathaleen’s Fall was decommissioned and from 1970 onwards total trapping was carried out at three eel traps providing a long term dataset for recruitment to the Erne. The downward trend in recruitment of elvers noted in the River Shannon and at other recruitment monitoring stations in Europe during the mid 1980s and 1990s was not evident at Cathaleen’s Fall (Moriarty and Tesch, 1996; Dekker, 2000) and between 1970 and 2002 elver catches averaged 1300 kg per annum (Matthews et al., 2002) with a total catch of over 4000 kg recorded in 1994 (Matthews et al., 1999). However, in 2008, 2009 and 2010 the three lowest annual catches in the entire Cathaleen’s Fall data series were recorded and the average annual catch between 2003 and 2010 was just 293 kg.

The River Lee was harnessed for electricity generation between 1953 and 1957 when the Carrigadrohid and Inniscarra generating stations were commissioned. No eel specific fish passage or trap and transfer facilities were incorporated in the construction of the dams and periodic ascent by juvenile eels to the reservoirs upstream must have occurred via the Borland lift facilities (McCarthy et al., 2008b). In 2008 an elver pass trap was installed below the Inniscarra dam to enhance the level of eel recruitment to the upper catchment to add to the knowledge of eel biology in this relatively unstudied river system.

Monitoring of recruitment is essential for evaluating the overall success of the mitigation measures adopted by European countries in accordance with the EC regulation for the recovery of the eel stock (EC, 2007; Anon., 2008a). This current investigation was undertaken during the period 2008–2010 with a view to establishing the abundance, seasonal duration and variation in timing of eel recruitment to the Shannon, Erne and Lee river systems. Biological characteristics of migrating juvenile eels including length, weight and age of eels were also examined.
3.2 Study area

A detailed description of the study area is provided in Chapter 2. The investigation was undertaken at sites on the Shannon, Lee and Erne river systems (Figure 3.1). Eels were collected from juvenile eel traps immediately downstream of the Ardnacrusha generating station and the Parteen regulating weir on the River Shannon. On the River Erne there are three eel traps located at Cathaleen’s Fall generating station which is situated at the tidal limit of the Erne estuary. One trap is located on the northern bank (high level trap) the second is located on the G5 platform and the third is located on the downstream platform. On the River Lee one juvenile eel trap, installed in September 2008, is located approximately 180 meters downstream of the Inniscarra generating station.

![Map of Ireland showing the locations of hydroelectricity facilities where fixed juvenile eel traps are used](image)

**Figure 3.1** Map of Ireland showing the locations of hydroelectricity facilities where fixed juvenile eel traps are used
3.3 Materials and methods

3.3.1 Juvenile eel abundance and migration timing

The juvenile eel traps used on the Shannon, Lee and Erne river systems are based on a design by O’Leary (1971), sometimes referred to as “Irish type elver traps” (Haro et al., 2000; Jessop, 2003a). The trap consists of a gently sloping ramp covered with a climbing substrate that leads to a holding tank positioned at the top of the ramp. There is a constant flow of water (c. 30 litres per minute\(^{-1}\)) down the face of the ramp that stimulates the rheotactic tendencies of juvenile eels migrating upriver close to the bank. Once eels ascend to the top of the ramp they are flushed into the holding tank where they are held until they are transported in aerated tanks for stocking upstream.

At Ardnacrusha on the River Shannon the juvenile eel trapping facility consists of three sections, a concrete ramp and a gulley that leads to a pre-fabricated trap (Plate 3.1). The concrete ramp is covered with Tensar \textregistered Mat which is a polyethylene mesh material designed to control soil erosion but in this instance it is used as a climbing substrate that allows elvers to pass through it easily (Reynolds et al., 1994). Once the eels ascend past the ramp’s crest they enter a gulley leading to the base of a prefabricated trap. The trap, manufactured by “Fish-Pass” in France, is composed of a fiberglass ramp with a base of variably concentrated plastic bristles and additional Tensar \textregistered Mat that acts as a climbing substrate. A horizontal spray bar located at the top of the ramp directs water to the ramp and also into the holding tank. Once the eels reach the top of the ramp they are washed into the holding tank (O’Connor, 2003).

The trap at Parteen (Plate 3.2) on the River Shannon consists of a metal ramp with a marine plywood base on which tufts of plastic bristles are laid to act as climbing substrate for the ascending eels. The water needed to create the attraction flow on the ramp is supplied from the eel holding tank where it overflows through a fine mesh grid preventing eels from escape. The traps used on the Erne River system at Cathaleen’s Fall (Plate 3.3) consist of concrete ramps/gulleys 70 cm in width, containing stones
(approximately 3–5 cm in size) that act as the climbing substrate, leading to the holding tanks (Copley, 1999; Matthews et al., 1999). At Inniscarra on the River Lee the juvenile eel trap (Plate 3.4) consists of a fiberglass ramp covered with plastic bristles leading to the holding tank.

Eels were removed from the traps when substantial numbers had accumulated and removal of eels was therefore irregular. The traps were emptied at least once per week on average and more frequently during periods of peak migration.

### 3.3.2 Length, weight and condition

Samples for length measurement were taken at irregular intervals throughout the migratory season. Eels were anaesthetised using a 10:1 solution of ethanol (70%) and clove oil following the method described by Durif et al. (2006) All eels present in the juvenile eel traps on the day of sampling were measured [total length ($L_T$) to the nearest mm]. In 2009 and 2010 individual weights of eels from unbiased samples collected at the Ardnacrusha ($N = 2$) and Parteen ($N = 6$) eel traps were recorded. Eels were weighed to the nearest 0.01 g. Following recovery from the anaesthetic all eels except a sub-sample retained for age determination and further laboratory examination were subsequently released in water above the dams.

Fulton’s Condition Factor ($K$) was calculated as follows:

$$K = 10^3 \times \frac{W}{L^3}$$

Where $W$ is weight in grams and $L$ is length in centimetres.

Differences in length, weight and condition factor among eel samples were tested using the nonparametric Mann-Whitney $U$-test (M-W $U$) for 2 samples and the nonparametric Analysis of Variance Kruskal-Wallis test (Kruskal-Wallis ANOVA) for 3 or more samples. Where significant difference among length frequency distributions were found using the Kruskal-Wallis test, the non-parametric Dunn's post hoc test (Dunn,
1964) was used to determine which length frequency distributions were significantly different.

The relationship between length and weight of eels is expressed by the conventional formula:

\[ W = aL^b, \]

and using the logarithmic transformation:

\[ \log_{10}W = a + b(\log_{10}L) \]

where \( W \) is weight, \( L \) is length, \( a \) is a proportional constant and \( b \) is an exponent, usually between 2.5 and 4.0, which describes the curve of the relationship and the slope of the line in the case of log transformed data (Pope and Kruse, 2007). The parameters “\( a \)” and “\( b \)” were estimated by least squares regression. The null hypothesis that \( b = 3 \) (indicating an isometric pattern of growth) was tested using the t test as described by Zar (1999). A t test was used to examine whether “\( b \)”, the slope of the \( \log_{10}W - \log_{10}L \) plot was different for two samples as described by Fowler (1998). The normality of the “\( b \)” distribution was tested by means of a Kolmogorov-Smirnov test.

Statistical analysis was performed using the programme IBM SPSS Statistics 18 (SPSS Inc., Chicago, IL). Dunn’s post hoc tests were performed using GraphPad InStat version 3.10 for Windows (GraphPad Software Inc., San Diego, CA.) A significance level of \( p < 0.05 \) was used in all tests.
3.3.3 Age determination

During the migratory periods of 2008, 2009 and 2010 otoliths were obtained from samples of eels collected from the Shannon and Lee juvenile eel traps for age determination. Eels were euthanised on the day of sampling using a 1:10 solution of clove oil dissolved in ethanol (70%). An overdose (5 ml) of this solution was added to a 10 l water bath in which the eels were immersed. The eels were maintained in the anaesthetic solution for 5–10 minutes after cessation of opercular movement to ensure they had expired (Neiffer and Stamper, 2009).

The right and left saggital otoliths were removed, cleaned with water and stored in labelled otolith trays. Otoliths were allowed to dry naturally for at least a week before they were prepared for age reading. The otoliths were then immersed in cedarwood oil for 48 hours and allowed to clear. The otoliths were then placed on a microscope slide and read using a binocular microscope at 40 x magnification, using reflected light against a black background (Cullen and McCarthy, 2003; Melià et al., 2006). Otoliths were then rinsed in alcohol and allowed to dry naturally before being stored again for subsequent readings.

The continental age (number of years in freshwater) of the fish was calculated by counting the number of annuli present after the entrance into freshwater, which is marked by a double ring (Moriarty, 1986; Naismith and Knights, 1988; Acou et al., 2009). Each otolith was aged using three readings and otoliths were read blind, i.e. with no reference to the eel they came from, or to any information on previous readings made on that otolith in order to minimise human error (Panfili et al., 1990). Only ages that agreed on two successive readings were used in further analysis. Growth rate was estimated as $L_T$ per age and was expressed in mm year$^{-1}$. 

3.4 Results

3.4.1 Migration timing and juvenile eel abundance

Ardnacrusha, River Shannon
The Ardnacrusha trap was in operation continuously in each year of from early May until the end of the juvenile eel migration in late September. The total catches recorded in each month for the years 2008–2010 are shown in Table 3.1 to Table 3.3.

In 2008 the first date of capture of juvenile eels at Ardnacrusha was recorded on June 25th and the final date of capture was on September 9th. 75 days elapsed between the first and last date. In total 6.846 kg of eels were captured (Table 3.1) and the largest catches were recorded in June and September. During 2009 the total recorded catch was merely 879 g (Table 3.2) and a period of 44 days elapsed between the first and last recorded capture. This catch comprised of 614 g recorded on June 16th and a second catch of 216 g recorded on July 29th. In 2010 the first catch was recorded on June 4th and the total catch for the year was substantially higher compared to other years at 49.732 kg (Table 3.3). The catch recorded during 2010 along with the cumulative catch is shown in Figure 3.2. In 2010 relatively small catches were recorded in early June and increased catches were made from mid June until the end of July. Catches decreased again in August and the final catch was recorded on September 2nd. 50% of the catch was recorded by mid July and over 98% of the catch was made by August 20th. A period of 89 days elapsed between the date of the first and last recorded capture of eels.

An estimate of the number of eels captured in the Ardnacrusha juvenile eel trap in 2008 and 2010 is given in Table 3.4 based on the mean numbers per kg calculated from length measurements of the eels sampled in each month of the migration period in those years. In 2009 the total catch of juvenile eels was low (879 g) and all of the eels captured were sampled giving a complete count of the numbers present which was just 322 eels.
Parteen, River Shannon

The Parteen trap was in operation in each year from early May. In 2008 the trap was operated until the end of October to facilitate a small number of juvenile eels migrating late that year while in 2009 and 2010 the migration had come to an end by early September and the trap was operated until the end of the month. The total catches recorded in each month for the years 2008–2010 are shown in Table 3.5 to Table 3.7 and Figure 3.5 to Figure 3.3 show the total catch over the migration period for each year.

In 2008 first date of capture of juvenile eels was May 8th and the last was recorded on the October 31st. 177 days elapsed between the first and the last dates of recorded captures at the trap. In 2009 and 2010 the timing and duration of the eel migration were broadly similar to each other. The dates that the first captures of eels were recorded were 8/6/2009 and 4/6/2010 and the number of days that elapsed between the first and last recorded captures was 94 (2009) and 90 (2010). Table 3.8 gives the dates of the earliest and latest recorded catches in each year and the water temperature recorded at the Parteen weir on those dates. Water temperature ranged from 13.8–17.5ºC when the first catch was recorded.

The juvenile eel migration in 2008 was exceptional in comparison to the other two years in terms of the total catch recorded and its timing and duration. The total annual catch in 2008 (1305.770 kg) was more than 4 times the combined catch of 2009 and 2010. In 2008 148.500 kg of eels were captured by the end of May, more than the total annual catch recorded in 2009 (138.910 kg) and just 13.050 kg less than the total annual catch in 2010 (161.550 kg).

In 2008 there was a period of intense migration activity in August and 820 kg of eels were captured, which represented 63% of the total catch for that year. 95% of the total annual catch was recorded by August 22nd and relatively small catches were made throughout September and up until the last catch was recorded on October 30th. In 2009
and 2010 50% of the total annual catch of eels were recorded by late June in each year and 95% of the total annual catch was captured by late July (2009) and early August (2010). The cumulative percentage of total catch with time for each year is shown in Figure 3.6. The exceptional catch recorded in August 2008 accounted for 51% of the total catch at Parteen for the period 2008 to 2010.

An estimate of the number of eels captured in each month in the Parteen trap for the years 2008–2010 is shown in Table 3.9 based on mean monthly numbers per kg calculated from length measurements of the eels sampled. The estimate of numbers of eels captured in October 2008 was arrived at using the mean monthly numbers per kg from September. More than 2.4 times as many eels were captured in the month of August 2008 alone than were captured for the entire migratory period during both 2009 and 2010 combined.

**Cathaleen’s Fall, River Erne**

The juvenile eel catch data for the years 2008–2010 are shown below in Figure 3.8 to Figure 3.10 and the total catches recorded in each month for the years 2008–2010 are shown in Table 3.10 to Table 3.12. Cumulative percentages of total catches with time are shown in Figure 3.11.

The timing and duration of the juvenile eel migration varied considerably between years. In 2008 the first catch was recorded on May 30th. 58 days elapsed between the date of the first and last recorded capture and this was the shortest migration period of the 3 years. The total annual catch was 36.361 kg and this was also the lowest of the 3 years. The majority of the catches (31.687 kg) were made in June and the catches made in July were progressively smaller until the final catch was recorded on July 28th. This was the earliest end to the migration out of the 3 years. The first catch in 2009 was recorded 3 days earlier than in 2008 on May 27th and 97 days elapsed before the last catch was recorded on September 9th. In total 85 kg of eels were captured in 2009 and
the largest catches were made in June and July. 50% of the total annual catch was collected by June 19\textsuperscript{th} and 95% of the catch was made by August 7\textsuperscript{th}. In 2010 the first catch was recorded on April 29\textsuperscript{th}, approximately one month earlier than in the other two years. The last catch was recorded 108 days later on August 16\textsuperscript{th}. The total annual catch for 2010 was 93.86 kg which was the highest of the 3 years. The majority of eels were captured in May, June and July and 50% of the catch was collected June 7\textsuperscript{th}.

**Inniscarra, River Lee**

A juvenile eel trap was installed below the Inniscarra generating station in September 2008 and operated until mid October of that year. In 2009 and 2010 the trap was put in operation early in May and ran continuously until the end of September.

In 2008 a catch of only 17 eels (mainly of elvers and small juvenile eels) were collected from the trap on October 14\textsuperscript{th}. It is probable that the upstream migration of eels that year at Inniscarra was coming to an end when the trap was put in operation. During 2009 a total weight of 23.890 kg of juvenile eels were captured in the Inniscarra trap with the first catch recorded on July 9\textsuperscript{th} and the last on September 11\textsuperscript{th} (Figure 3.12). The majority of eels were captured from late July to early August and after August 12\textsuperscript{th} only very small quantities of eels were captured. In 2010 the catch from the Inniscarra trap was merely 691 g, with the majority of catches (668 g) recorded during July.
Chapter 3

3.4.2 Length, weight and condition

Ardnacrusha, River Shannon
Samples (N = 9) for length measurement were taken from the Ardnacrusha juvenile eel trap at irregular intervals during the migration period in each of the years 2008 to 2010. The eels captured at Ardnacrusha during this period ranged from 60 to 224 mm $L_T$ with a mean ± SD of 93.5 ± 31.3 mm.

In 2008 a total of 1200 eels were measured for length over 5 separate dates between July 1st to September 9th. Descriptive statistics for these samples are shown in Table 3.13 and a percentage length frequency distribution of the pooled data is shown in Figure 3.13. The eels ranged from 60 to 198 mm $L_T$ with a mean ± SD of 84.0 ± 21.6 mm. Analysis of variance showed that the lengths of eels from the 5 sampling dates in 2008 were significantly different ($H = 81$, d.f. = 4, $p < 0.05$). Post hoc analysis showed that no significant difference occurred between the lengths of eels sampled in July ($p > 0.05$) when median length was 87 mm and 84 mm. Similarly, no significant difference occurred between the two samples collected in August when median length was 72 mm and 73 mm. There was a significant difference in the lengths of eels sampled between the months July and August and September. Eels in the July and September (median = 76 mm) samples were significantly larger than those captured in August (Figure 3.14).

During 2009 two samples were collected, the first on June 16th and the second on July 29th. In total 322 eels were measured for length and the eels ranged from 70 to 224 mm $L_T$ with a mean ± SD of 141.4 ± 24.0 mm. Descriptive statistics for these samples are shown in Table 3.14 and a percentage length frequency distribution of the pooled data is shown in Figure 3.15. There was a significant difference in lengths of eels from the 2 sampling dates in 2009 ($U = 10248$, d.f. = 1, $p < 0.05$) with larger eels present in July sample compared to the June sample.
In 2010 samples were collected on 2 dates, June 18th and August 4th. Descriptive statistics for these samples are shown in Table 3.15 and a percentage length frequency distribution of the pooled data is shown in Figure 3.16. The eels ranged from 62 to 164 mm $L_T$ with a mean ± SD of 75.4 ± 13.1 mm. There was a significant difference in lengths of eels from the 2 sampling dates in 2010 ($U = 5482$, d.f. = 1, $p < 0.05$) with larger eels present in August sample compared to the June sample, a finding similar to that observed in 2009 where larger eels were found in samples taken later in the migratory season.

Analysis of variance showed that the lengths of eels sampled at Ardnacrusha during 2008, 2009 and 2010 were significantly different ($H = 69$, d.f. = 2, $p < 0.05$) and post hoc analysis showed that significant differences occurred between all of the years ($p < 0.05$). Eels sampled in 2008 and 2010 were similar in terms of mean length and the size range of eels present in the samples, with elvers and small bootlace eels comprising the majority of the catch (Figure 3.13 and Figure 3.16). In 2009 (Figure 3.15) larger bootlace eels were predominant in the low catch that was recorded in that year and the mean length (142 mm) was considerably higher compared to the other two years.

Juvenile eel weights recorded in samples collected at Ardnacrusha ranged from 0.2–11.6 g on June 16th 2009 and from 0.2 to 2.8 g on August 4th 2010 (Table 3.16). Juvenile eel weights increased with increasing length in a curvilinear manner in 2009 and 2010 (Figure 3.17 and Figure 3.19 respectively). The predictive linear equations describing the relationship between length and weight using the log method for both samples are shown in Figure 3.18 and Figure 3.20. The slopes of the regression lines in 2009 ($b = 3.08$) and 2010 ($b = 3.17$) were not significantly different from 3 ($p > 0.05$ in both cases) indicating an isometric pattern of growth and there was no significant difference in $b$ between 2009 and 2010 ($t = 0.52$, d.f. = 375, $p > 0.05$). Fulton’s condition factor ($K$) was calculated for the eels sampled and descriptive statistics are given in Table 3.17.
Condition factor ($K$) ranged from 0.44 to 1.37 and the mean condition factor for both samples combined was 0.87.

**Parteen, River Shannon**

Samples ($N = 27$) for length measurement were taken from the Parteen juvenile eel trap at irregular intervals during the migration period in each of the years 2008 to 2010. Eels captured ranged from 76 to 329 mm $L_T$ with a mean ± SD of 152.4 ± 38.4 mm.

In 2008 samples were collected on 12 separate dates. A total of 3,857 eels were collected between June and September and descriptive statistics for these samples are shown in Table 3.18. A percentage length frequency distribution of the pooled data is shown in Figure 3.21. These eels ranged from 80 to 329 mm $L_T$ with a mean ± SD of 154.9 ± 37.9 mm. Analysis of variance showed that the lengths of eels from the 12 sampling dates in 2008 were significantly different ($H = 489$, d.f. = 11, $p < 0.05$). Post hoc analysis showed that no significant difference occurred in the lengths of eels sampled in June ($p > 0.05$). The median length of eels from the June samples ranged from 140 to 150 mm. Significant differences in the length occurred between all of the samples taken in July ($p > 0.05$) when median length ranged from 137 to 177 mm and between all of the samples taken in August when median length ranged from 132 to 149 mm ($p > 0.05$). One sample was collected in September (median length = 175 mm) and this was significantly different to all other samples ($p < 0.05$). There was no consistent trend in the variation of the length frequency distributions between samples taken at different dates in the migration period (Figure 3.22), however, mean length increased in each of the 4 samples taken from August 14th to September 10th.

During 2009 samples were collected on 10 separate dates between June and August. No samples were taken in September as the migration came to an end early in the month and only a relatively small number of eels were captured. In total 811 eels were measured for length in 2009 and descriptive statistics for these samples are given in
(Table 3.19). Eels ranged from 76 to 293 mm $L_T$ with a mean ± SD of 142.1 ± 34.6 mm. A percentage length frequency distribution of the pooled data from these samples is shown in Figure 3.23. Analysis of variance showed that the lengths of eels from the 10 sampling dates in 2009 were significantly different ($H = 86$, d.f. = 9, $p < 0.05$). One sample was collected in June 2009. The median length of the eels sampled was 147 mm and this was not significantly different from any of the samples collected in July ($p < 0.05$). No significant difference between the lengths of eels sampled in July was found and the median length ranged from 136 to 147 mm. Similarly, in August no significant difference between the lengths of eels sampled was found ($p > 0.05$). Median length of the eels from the samples collected in August ranged from 118 to 127 mm. Significant differences in the lengths of eels sampled were found between eels sampled in June and August and between eels sampled in July and August. There was no consistent trend in the variation of the length frequency distributions (Figure 3.24) except the mean lengths of eels in the samples collected in August were all lower than those of samples collected in June and July.

Samples were collected on 5 separate occasions in 2010 between June and September. A total of 372 eels were measured for length and descriptive statistics for these samples are given in Table 3.20. These eels ranged from 81 to 316 mm $L_T$ with a mean ± SD of 151.0 ± 46.8 mm. A percentage length frequency distribution of the pooled data from these samples is shown in Figure 3.25. Analysis of variance showed that the lengths of eels from the 5 sampling dates in 2010 were significantly different ($H = 37$, d.f. = 9, $p < 0.05$). Mean length varied between samples and a similar pattern to that observed in 2008 was apparent with an increase in mean length in the samples collected in July, August and September (Figure 3.26). The mean length of the eels (N = 29) collected in September was considerably higher in comparison to the other samples taken in earlier months.
Analysis of variance showed that the lengths of eels sampled at Parteen during 2008, 2009 and 2010 were significantly different ($H = 86$, d.f. = 2, $p < 0.05$) and post hoc analysis showed that the difference occurred between eels sampled in 2008 and 2009 ($p < 0.05$) where median length was significantly higher in 2008.

There was a significant difference between the lengths of eels capture in Parteen and Ardnacrusha in 2008 ($U = 199304$, d.f. = 1, $p < 0.05$) and 2010 ($U = 1687$, d.f. = 1, $p < 0.05$). In 2009, however, there was no significant difference ($U = 138240$, d.f. = 1, $p > 0.05$).

Individual eel weights were recorded from 4 samples collected at Parteen in 2009 and ranged from 0.5 to 23.0 g. In 2010 samples were collected on 2 dates and individual weights ranged from 0.5 to 36.0 g. Descriptive statistics for all samples are given in Table 3.21. Weight increased with increasing length in a curvilinear manner in 2009 and 2010 (Figure 3.27 and Figure 3.29 respectively) and the predictive linear equations describing the relationship between length and weight using the log method for both samples are shown in Figure 3.28 and Figure 3.30. The slopes of the regression lines in 2009 ($b = 3.22$) and 2010 ($b = 3.33$) were not significantly different from 3 ($p > 0.05$ in both cases) indicating an isometric pattern of and there was no significant difference in $b$ between 2009 and 2010 ($t = 1.49$, d.f. = 366, $p > 0.05$). Fulton’s condition factor ($K$) calculated for eels sampled at Parteen ranged from 0.37 to 1.54 with a mean value of 1.02 for all the samples combined (Table 3.22).
Cathaleen’s Fall, River Erne
Site visits to the juvenile eel trap at Cathaleen’s Fall were carried out in 2008 and 2010. Samples of eels for measurement of length were taken on 2 consecutive dates in July of 2008. A total of 174 eels were measured in 2008 and the descriptive statistics from both sample dates is summarised in Table 3.23. These eels ranged from 61 to 172 mm $L_T$ with a mean ± SD of 72.4 ± 13.3 mm. The percentage length frequency of the pooled data from these samples is presented in Figure 3.31. Although the mean $L_T$ of the two samples were the same (72 mm) there was a significant difference between the lengths ($U = 1473$, d.f. = 1, $p < 0.05$) with the median $L_T$ of eels significantly higher in the July 27th sample. A much wider size range of eels were present in the July 28th sample due to the presence of a small number of larger bootlace eels.

In 2010 a sample of 124 eels was collected at Cathaleen’s Fall on July 12th, descriptive statistics of the data is provided in Table 3.23 and the percentage length frequency distribution is shown in Figure 3.32. The eels ranged from 54 to 218 mm $L_T$ with a mean ± SD of 87.2 ± 38.7 mm. No significant difference in length was observed between the eels sampled in 2009 (pooled data from 2 samples) and the eels sampled in 2010 ($U = 10275$, d.f. = 1, $p > 0.05$). In each year the samples were dominated by elvers with a much lower frequency of bootlace eels.

Inniscarra, River Lee
In 2008 a sample of eels were measured for length on one occasion on October 14th. The total catch was just 17 eels. The catch was made up mainly of elvers and small bootlace eels ranging in length from 78 to 110 mm with a mean ± SD of 92.0 ± 10.2 mm (Table 3.24, Figure 3.33). In 2009 eels were sampled on two dates, July 24th and August 19th. The eels ranged in length from 83 to 199 mm and and the percentage length frequency distribution of the pooled data is shown in Figure 3.34. The mean length of eels from each sample was similar at 133.7 mm and 129.5 mm respectively (Table 3.24) and there was no significant difference between the length frequency distributions of the two samples ($U = 2184$, d.f. = 1, $p > 0.05$).
In 2010 a sample of 83 eels were collected from the trap on July 20\textsuperscript{th}. The catch comprised of mainly elvers and small bootlace eels ranging in length from 81 to 152 mm with a mean ± SD of 113.6 ± 16.2 mm (Table 3.24). A percentage length frequency distribution is shown in Figure 3.35.

Analysis of variance showed that the lengths of eels sampled at Inniscarra during 2008, 2009 and 2010 were significantly different ($H = 100$, d.f. = 2, $p < 0.05$) and post hoc analysis showed that significant differences occurred between each year ($p < 0.05$) with larger eels more frequent in the 2009 and 2010 samples compared to 2008.
3.4.3 Age determination

**Ardnacrusha, River Shannon**

In 2008 otoliths from 25 eels (mean ± SD $L_T = 116.3 \pm 38.0$ mm, range = 67–192 mm) captured in the Ardnacrusha juvenile eel trap on July 18$^{th}$ were aged by examination of the saggital otoliths. Four year classes were present and no 0+ class elvers were observed. A length at age plot for the sample collected at Ardnacrusha is given in Figure 3.36. The mean length-at-age increased from 1+ to 3+ (Table 3.25). The results indicate an annual growth rate of 40 mm year$^{-1}$ within the limits of observed age classes 1+ to 3+.

**Parteen, River Shannon**

In 2008 otoliths from 50 eels (mean ± SD $L_T = 148.3 \pm 41.6$ mm, range = 80–256 mm) collected at the Parteen juvenile eel trap were examined using the same protocol. The eels were collected on June 6$^{th}$ ($N = 20$) and July 29$^{th}$ ($N = 30$). Seven year classes were observed and no 0+ group elvers were present. There was quite a large variation in length with age (Figure 3.37) as was seen in eels of 6 years of age that ranged in length from 152 to 256 mm. The mean length-at-age increased from 1+ to 5+ (Table 3.26). The results indicate an annual growth rate of 30 mm year$^{-1}$ within the limits of age groups 1+ to 5+.

**Inniscarra, River Lee**

In 2009 a sample of 25 eels (mean ± SD $L_T = 130.3 \pm 15.8$ mm, range = 96–158 mm) were collected from the Inniscarra juvenile eel trap on August 19$^{th}$. Six year classes were present and there were large variations in length with age. In the case of the eels of 4 years of age the length ranged from 112 to 157 mm. The smallest eel (96 mm in length) was aged 1+ and the remaining eels ranged in size from 112 to 158 mm and were aged 2+ to 6+ (Figure 3.38). The mean length at age data for the eels sampled is shown in Table 4.1. The mean length at age increased from 1+ to 3+ (Table 3.27). The results indicate an annual growth rate of 20.2 mm year$^{-1}$ within the limits of ages 1+ to 3+.
3.5 Discussion

The annual catches of elvers and juvenile eel at Ardnacrusha from 2008 to 2010 were remarkably low in comparison to peak catches recorded at the site in the past, such as a catch of 2.1 tonnes in 1997 (McCarthy et al., 1999) but they continued the pattern of variable but relatively poor catches observed since then. No elver catches were recorded at Ardnacrusha before the start of June in each of the years 2008–2010 whereas McCarthy et al. (1999) found that large catches were made as early as mid April in 1997. The timing of the first capture of eels at Parteen varied considerably in each year from May 8th in 2008 to June 8th in 2009 and the water temperature on the date of the first recorded catch varied from 13.8–17.5º C (Table 3.8). Moriarty (1986) also observed a wide variation in the start date of migration at Parteen ranging from May 31st to as late as June 24th. There was also a range of water temperatures recorded on first date of migration (13–18º C) in Moriarty’s study but in 5 of the 7 years examined migration began when water temperature was less than 15º C. White and Knights (1997a) found that on the River Thames in England juvenile eels were not caught in any quantity until water temperatures rose above 15–16º C in mid-June/early July and proposed that water temperature was critical in controlling migration. Similarly, at a site 35 km upstream of the mouth of the River Gudenå in Denmark, Dahl (1983) reported that the water temperature at the beginning of the juvenile eel migration ranged from 15–17º C. Migration of juvenile eels at Parteen continued into September in 2009 and 2010 and the water temperature on the date of the final recorded catch varied from 16º C (2009) to 15º C (2010). In 2008 juvenile eels continued to migrate until late October and the final catch was recorded on October 31st when the water temperature was 11.5º C. However, in that year the average water temperature recorded at Parteen in October was 13.1º C and the relatively warm water temperature may have had an influence on the continuation of the late season eel migration. Tesch (2003) has reported that with falling temperatures in the autumn, upstream migration of eels decreases and at temperatures below 10º C it halts almost completely.
Between 2009 and 2010 there was relatively little variation in the total annual catch at Parteen; 139 to 162 kg respectively. In those two years the majority of the eel catch was recorded in the months of June and July (Figure 3.6). In 2008, however, the total catch was 1306 kg, the highest recorded annual catch at Parteen since 1988 when a total catch of 1265 kg was made. There was an exceptional peak in migration activity at Parteen in August 2008 which was reflected by the high catch in the juvenile trap in that month (Table 3.5, Figure 3.3). The catch recorded in August 2008 accounted for 51% of the total catch at Parteen for the period 2008 to 2010. Moriarty (1986) reported that a catch of nearly 2,500 kg was made in 1980, and more than half of the total catch in that year was made in the first two weeks of August. That catch coincided with high river flow in the Kilmastulla River (a tributary of the River Shannon) in August of that year which was more than three times the monthly average (Moriarty, 1986). As in 1980, the high catch recorded in August 2008 also coincided with unusually high river flow. The water discharge from the Parteen reservoir into the lower River Shannon is maintained at the statutory minimum flow rate of 10 m$^3$ s$^{-1}$ but the flow in the lower river is also influenced by a number of tributaries, one of which is the Kilmastulla River that joins the lower River Shannon just below the Parteen regulating weir. Water discharge data for the Kilmastulla River was obtained from the Environmental Protection Agency (http://hydronet.epa.ie/hydronet.html) for the period 2008 to 2010 and as can be seen from the data presented in Figure 3.7 the mean monthly flow rate for August in 2008 was exceptionally high compared to the values observed in the following two years.

The onset of upstream migration of elvers at Cathaleen’s Fall on the River Erne was earlier than at Ardnacrusha on the River Shannon and the majority of the total catch was recorded before the end of July in each year in this study (Figure 3.11). Total annual catches varied between years (from 36 to 94 kg) but were remarkably low compared to previous catches considering that the 1970–2002 average annual catch was 1300 kg (Matthews et al., 2002). Similarly on the River Lee there was a wide variation in the total annual catch recorded at the trap that was installed at Inniscarra in late September 2008 but the values were low. The trap operated continuously throughout the migration
season in 2009 and 2010 and total annual catch ranged from 23.890 kg (2009) to just 691 g (2010). Prior to 2008 no trapping of migrating juvenile eels took place on the River Lee and recruitment to habitat upstream of the Inniscarra dam must have taken place via the Borland lift facilities (McCarthy et al., 2008b). One reason for the variable and low total annual catch may be that the location of the trap approximately 180 metres downstream of the dam (Plate 3.4) is not optimal and its effectiveness may be impaired as a result. The location of the downstream entrance of a juvenile eel trap is critical to its success (Solomon and Beach, 2004) and at Inniscarra it is possible that migrating juvenile eels are more attracted by the water discharge of the hydroelectric power station and Borland lift than the relatively weak attraction flow of the juvenile eel trap. In addition to this Moriarty (1999) reported that the persistent failure of efforts to establish a fyke net fishery in tidal waters of the Lee estuary in the past suggests that supply of elvers to the catchment is limited. However, future monitoring of the catches may be beneficial in providing an index of recruitment to the area of the catchment upstream of the Inniscarra dam.

In 2008 and 2010 the length structure of eels sampled at Ardnacrusha was significantly different from those collected at Parteen. This finding is in agreement with results of other European studies undertaken by Dahl (1983) and Legault (1996) cited by Ibbotson et al. (2002) where eels captured in traps closer to the sea include all sizes but tend to be dominated by smaller eels than eels trapped further upstream (Legault, 1996). Increase in mean $L_T$ is linked to a decrease in density from the tidal limit to the upstream habitat (Naismith and Knights, 1990b; Feunteun et al., 1998; Ibbotson et al., 2002). No significant difference was observed in the $L_T$ structure of eels from Ardnacrusha and Parteen in 2009 which could be explained by poor recruitment of elvers from the estuary to Ardnacrusha reflected in the low catch in the trap that year.

Moriarty (1986) found that there was a definite pattern to the variation in size of migrating eels at Parteen, with large eels predominating the catch in the first month of
the migration and small eels being scarce regardless of whether the migration begins early or late. Small eels were abundant in June if the migration had started in May but remained scarce in late seasons and were noticeably fewer when the migration season was coming to an end. A seasonal decrease in mean length of migrating elvers has been reported for a number of anguillid species (Haro and Krueger, 1988; McGovern and McCarthy, 1992a; Tzeng and Tsai, 1992; Jessop, 2003a). Seasonal declines in elver length during river entrance has been attributed to later arriving elvers averaging shorter (Haro and Krueger, 1988) and changes in physiology and behaviour associated with the movement into freshwater environments (Jessop, 2003a). White and Knights (1997a) found that mean length of elvers migrating in the River Thames decreased with advancing season until July when migratory activity was at its peak, and thereafter mean length increased slightly. The variation in size of migrating eels trapped at Parteen during this study did not follow such distinct a pattern as described by Moriarty (1986) or White and Knights (1997a), however, in 2008 (Figure 3.24) and 2010 (Figure 3.26) mean length increased towards the end of the migration period. In all of the other studies mentioned previously, except for Moriarty’s (1986), the samples were predominated by small elvers and mean lengths of the eels sampled were < 100 mm, whereas, at Parteen the majority of eels migrating are larger and older juvenile eels and there is a wide range of size (Figure 3.21) and age classes (Figure 3.37) present. Tesch (2003) analysed length frequencies of juvenile eels from the River Elbe in Germany and surmised that the relative decrease of smaller juvenile eels in autumn was due to a decrease in activity by smaller eels with falling temperatures and decreasing daylight.

The length–weight relationship of the eels sampled in 2009 and 2010 from Parteen and Ardnacrusha were described using a power function and ordinary least squares regression and in each case the exponent \( b \) of the power function and the slope of the regression line \( b \) was slightly higher (though not statistically significant) than 3 suggesting that the eels were in good condition, with the fish becoming “heavier for its length” as it grows larger (Tesch, 1968; Froese, 2006). A value of 3.22 was calculated for \( b \) using the data collected from the Parteen sample in 2009 which was identical to the
value recorded by Moriarty (1986) for a sample of eels of a similar size collected at Parteen in 1974. In each year the exponent $b$ calculated from the Parteen samples was higher than for eels sampled from Ardnacrusha. Similarly higher mean values for Fulton’s condition factor ($K$) were observed for the Parteen eels although $K$ is length dependent with $K$ increasing with increasing length, limiting comparison of the values to fish of similar length (Pope and Kruse, 2007).

At Cathaleen’s Fall generating station located at the tidal limit of the Erne estuary samples of eels collected from the juvenile eel traps were composed mainly of small elvers (< 100 mm $L_T$) (Figure 3.31 and Figure 3.32) but some bootlace eels up to 218 mm $L_T$ were present also. Samples were collected in July of 2008 and 2010 near the end of the migration and according to Matthews et al. (1999) the appearance of bootlace eels in the catch was a reliable indicator that the elver migration was coming to an end. The eels sampled from the Inniscarra juvenile eel trap ranged from 78 to 152 mm in length and were dominated by small bootlace eels (Figure 3.34 and Figure 3.35) broadly similar to those sampled from Parteen on the River Shannon and to riverine populations sampled by electrofishing downstream of the Inniscarra dam in the River Lee (McCarthy et al., 2008b) and (Chapter 6, this study).

In the sample of eels collected for age determination at the Ardnacrusha juvenile eel trap in 2009 no 0+ aged elvers were present and the observed ages ranged from 1+ to 4+ (Table 3.25). The sample size was relatively small ($N = 25$) and not representative of the entire size range of eels that were captured in the juvenile eel trap at Ardnacrusha between 2008 and 2011. It could be expected that 0+ aged elvers are captured in the trap as eels as small as 60 mm (Table 3.13) have been observed in samples collected for length measurement. The mean length of elvers aged 1+ was 80.0 mm which is lower than the mean length of aged 1+ elvers from the Frémur River in France (Acou et al., 2009) and the Thames River in England (Naismith and Knights, 1988). Aprahamian (2000), however, found elvers aged 1+ from tributaries of the lower River Severn in
England as small as 80 mm and similarly Moriarty (1986) found elvers (70 to 79 mm \(L_T\)) at Parteen on the River Shannon that were aged 1+. In the latter study it was noted that the majority of eels less than 90 mm were aged 1+. In studies on eels from Spain (Fernández-Delgado et al., 1989) and Portugal (Gordo and Jorge, 1991) mean length of 1+ aged eels has been as high as 134 and 172 mm respectively. In both of these studies it was suggested the high growth rate was related to the low latitude and brackish environment. The mean length of eels in the sample from Ardnacrusha increased from age 1+ to 3+ but the annual growth increments were irregular (Table 3.25, Figure 3.36).

The results of the age determinations made from the samples collected at Parteen in this study were compared to those recorded by Moriarty (1986) for migrant eels captured at Parteen in 1974. In the present study 6 year classes were present in sample collected as opposed to 10 year classes recorded by Moriarty (1986). In both studies no 0+ elvers were present and the annual growth rate determined in this study (30 mm year\(^{-1}\)) was slightly higher than that found by Moriarty (27 mm year\(^{-1}\)) for the same age classes. McCarthy et. al. (1994a) recorded an annual growth rate of 28 mm year\(^{-1}\) for eels aged 1+ to 5+ collected in the lower Shannon downstream of the Parteen regulating weir by electrofishing in 1993. A similar annual growth rate (28.7 mm year\(^{-1}\)) were determined by Naismith and Knights (1988) in their study of migrating elvers and juvenile eels on the River Thames. As in Moriarty’s study a wide variation in length with age was apparent in the Parteen sample and annual growth increments were irregular (Figure 3.37, Table 3.26).

At Inniscarra no 0+ aged elvers were present in the sampled collected and the majority of eels present (19 of the 25 sampled) were aged 3+ and 4+ (Table 3.27 and Figure 3.38) There was a large overlap in eel length between these adjacent age classes which is a finding frequently reported in studies of anguillids (Moriarty, 1986; Panfili et al., 1990; Mallawa and Lecomte-Finiger, 1992) and the mean length of age 3+ eels was higher than that of 4+ eels which may be a result of the small sample size (\(N = 25\)) examined.
The annual growth rate of 40 mm year\(^{-1}\) for eels sampled at Ardnacrusha was high in comparison to some studies of Irish eels (McCarthy et al., 1994a; Poole and Reynolds, 1996a) and it was also higher than the annual growth rate determined for eels from Parteen (30 mm year\(^{-1}\)) and Inniscarra (20.2 mm year\(^{-1}\)) in this study. There is a wide range in the annual growth rates reported for Irish, British and continental European *Anguilla anguilla* populations. Published annual growth rates of eels from other European studies cited by Aprahamian (2000) range from 14 to 152 mm per year\(^{-1}\). Moriarty (1973) found a high growth rate (40.5 mm year\(^{-1}\)) in the eels aged 5+ to 10+ sampled from the lakes in the Erne catchment and a study undertaken by Naismith and Knights (1990a; 1993) found a variation of 33.8–66.2 mm year\(^{-1}\) in the growth rate of eels from the Thames. Naismith and Knights (1993) attributed the variation in growth rates to habitat preferences and eel size with smaller migrants (< 250 mm) exhibiting the lowest growth rate (33.8 mm year\(^{-1}\)). In the Frémur River in northwest France Acou et al. (2009) found the annual growth rate for elvers and larger juvenile eels of a similar size range to those captured at Ardnacrusha was 48.1 mm year\(^{-1}\).

Factors suggested to influence growth rate include productivity of the water body, water temperature and size and demographics of the eel population (Panfili et al., 1994; Poole and Reynolds, 1996a; Tesch, 2003) and significant variation in all of these factors occurs between the locations where eels were sampled in this study. It can be hard to determine influences on eel growth from ecological studies (Tesch, 2003). Aprahamian (2000), for example, investigated the effect of eel density and biomass on the growth rate of eels ranging in length from 63 to 625 mm at 15 sites on tributaries of the lower Severn in England and found that neither factor had a significant effect on the growth rate.
### Chapter 3

#### 3.6 Tables

**Table 3.1** Juvenile eel catch (kg) recorded at Ardnacrusha during 2008

<table>
<thead>
<tr>
<th>Month</th>
<th>Weight (kg)</th>
<th>Cumulative Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>2.110</td>
<td>2.110</td>
</tr>
<tr>
<td>July</td>
<td>1.194</td>
<td>3.304</td>
</tr>
<tr>
<td>August</td>
<td>1.148</td>
<td>4.452</td>
</tr>
<tr>
<td>September</td>
<td>2.394</td>
<td>6.846</td>
</tr>
</tbody>
</table>

**Table 3.2** Juvenile eel catch (kg) recorded at Ardnacrusha during 2009

<table>
<thead>
<tr>
<th>Month</th>
<th>Weight (kg)</th>
<th>Cumulative Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>0.613</td>
<td>0.613</td>
</tr>
<tr>
<td>July</td>
<td>0.266</td>
<td>0.879</td>
</tr>
</tbody>
</table>

**Table 3.3** Juvenile eel catch (kg) recorded at Ardnacrusha during 2010

<table>
<thead>
<tr>
<th>Month</th>
<th>Weight (kg)</th>
<th>Cumulative Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>17.530</td>
<td>17.530</td>
</tr>
<tr>
<td>July</td>
<td>26.108</td>
<td>43.638</td>
</tr>
<tr>
<td>August</td>
<td>5.909</td>
<td>49.547</td>
</tr>
<tr>
<td>September</td>
<td>0.185</td>
<td>49.732</td>
</tr>
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</table>
Table 3.4 Estimate of numbers of young eels caught per month at Ardnacrusha in 2008, 2009 and 2010 (weight x mean number of eels per kg)

<table>
<thead>
<tr>
<th>Month</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>2,719</td>
<td>227</td>
<td>46,131</td>
</tr>
<tr>
<td>July</td>
<td>1,269</td>
<td>105</td>
<td>68,705</td>
</tr>
<tr>
<td>August</td>
<td>1,640</td>
<td>0</td>
<td>15,550</td>
</tr>
<tr>
<td>September</td>
<td>3,420</td>
<td>0</td>
<td>486</td>
</tr>
<tr>
<td>Total</td>
<td>8,868</td>
<td>332</td>
<td>130,872</td>
</tr>
</tbody>
</table>
Table 3.5 Juvenile eel catch (kg) recorded at Parteen during 2008

<table>
<thead>
<tr>
<th>Month</th>
<th>Weight (kg)</th>
<th>Cumulative Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>148.500</td>
<td>148.500</td>
</tr>
<tr>
<td>June</td>
<td>161.570</td>
<td>310.070</td>
</tr>
<tr>
<td>July</td>
<td>123.630</td>
<td>433.700</td>
</tr>
<tr>
<td>August</td>
<td>820.330</td>
<td>1254.030</td>
</tr>
<tr>
<td>September</td>
<td>37.390</td>
<td>1291.420</td>
</tr>
<tr>
<td>October</td>
<td>14.350</td>
<td>1305.770</td>
</tr>
</tbody>
</table>

Table 3.6 Juvenile eel catch (kg) recorded at Parteen during 2009

<table>
<thead>
<tr>
<th>Month</th>
<th>Weight (kg)</th>
<th>Cumulative Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>90.500</td>
<td>90.500</td>
</tr>
<tr>
<td>July</td>
<td>46.630</td>
<td>137.130</td>
</tr>
<tr>
<td>August</td>
<td>1.630</td>
<td>138.760</td>
</tr>
<tr>
<td>September</td>
<td>0.150</td>
<td>138.910</td>
</tr>
</tbody>
</table>

Table 3.7 Juvenile eel catch (kg) recorded at Parteen during 2010

<table>
<thead>
<tr>
<th>Month</th>
<th>Weight (kg)</th>
<th>Cumulative Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>104.520</td>
<td>104.520</td>
</tr>
<tr>
<td>July</td>
<td>45.210</td>
<td>149.730</td>
</tr>
<tr>
<td>August</td>
<td>11.700</td>
<td>161.430</td>
</tr>
<tr>
<td>September</td>
<td>0.120</td>
<td>161.550</td>
</tr>
</tbody>
</table>
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Table 3.8 Dates of first and last recorded capture of eels at Parteen and the water temperature (°C) on given dates

<table>
<thead>
<tr>
<th>Year</th>
<th>Date of first recorded capture</th>
<th>Temperature</th>
<th>Date of last recorded capture</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>8 May</td>
<td>13.8</td>
<td>31 October</td>
<td>11.5</td>
</tr>
<tr>
<td>2009</td>
<td>8 June</td>
<td>17.5</td>
<td>11 September</td>
<td>16.0</td>
</tr>
<tr>
<td>2010</td>
<td>4 June</td>
<td>17.4</td>
<td>3 September</td>
<td>17.2</td>
</tr>
</tbody>
</table>

Table 3.9 Estimate of numbers of young eels caught per month at Parteen in 2008, 2009 and 2010 (weight x mean number of eels per kg)

<table>
<thead>
<tr>
<th>Month</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>21,000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>June</td>
<td>38,000</td>
<td>23,000</td>
<td>26,000</td>
</tr>
<tr>
<td>July</td>
<td>24,000</td>
<td>12,000</td>
<td>6,000</td>
</tr>
<tr>
<td>August</td>
<td>171,000</td>
<td>794</td>
<td>2,000</td>
</tr>
<tr>
<td>September</td>
<td>5,000</td>
<td>63</td>
<td>29</td>
</tr>
<tr>
<td>October</td>
<td>2,000</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>261,000</td>
<td>35,857</td>
<td>34,029</td>
</tr>
</tbody>
</table>
Table 3.10 Juvenile eel catch (kg) recorded at Cathaleen’s Fall during 2008

<table>
<thead>
<tr>
<th>Month</th>
<th>Weight (kg)</th>
<th>Cumulative Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>2.240</td>
<td>2.240</td>
</tr>
<tr>
<td>June</td>
<td>31.687</td>
<td>33.927</td>
</tr>
<tr>
<td>July</td>
<td>2.434</td>
<td><strong>36.361</strong></td>
</tr>
</tbody>
</table>

Table 3.11 Juvenile eel catch (kg) recorded at Cathaleen’s Fall during 2009

<table>
<thead>
<tr>
<th>Month</th>
<th>Weight (kg)</th>
<th>Cumulative Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>3.500</td>
<td>3.500</td>
</tr>
<tr>
<td>June</td>
<td>51.909</td>
<td>55.409</td>
</tr>
<tr>
<td>July</td>
<td>25.200</td>
<td>80.609</td>
</tr>
<tr>
<td>August</td>
<td>4.200</td>
<td>84.809</td>
</tr>
<tr>
<td>September</td>
<td>0.200</td>
<td><strong>85.009</strong></td>
</tr>
</tbody>
</table>

Table 3.12 Juvenile eel catch (kg) recorded at Cathaleen’s Fall during 2010

<table>
<thead>
<tr>
<th>Month</th>
<th>Weight (kg)</th>
<th>Cumulative Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>11.590</td>
<td>11.590</td>
</tr>
<tr>
<td>May</td>
<td>31.249</td>
<td>42.839</td>
</tr>
<tr>
<td>June</td>
<td>21.022</td>
<td>63.861</td>
</tr>
<tr>
<td>July</td>
<td>24.090</td>
<td>87.951</td>
</tr>
<tr>
<td>August</td>
<td>5.900</td>
<td><strong>93.851</strong></td>
</tr>
<tr>
<td>Date</td>
<td>N</td>
<td>Mean</td>
</tr>
<tr>
<td>------------</td>
<td>----</td>
<td>------</td>
</tr>
<tr>
<td>1/7/08</td>
<td>134</td>
<td>93.1</td>
</tr>
<tr>
<td>18/7/08</td>
<td>223</td>
<td>94.6</td>
</tr>
<tr>
<td>11/8/08</td>
<td>304</td>
<td>78.3</td>
</tr>
<tr>
<td>22/8/08</td>
<td>200</td>
<td>80.9</td>
</tr>
<tr>
<td>9/9/08</td>
<td>339</td>
<td>80.2</td>
</tr>
<tr>
<td>Total</td>
<td>1200</td>
<td>84.0</td>
</tr>
</tbody>
</table>

**Table 3.14** Summary of length data for Ardnacrusha juvenile eels 2009 by date sampled

<table>
<thead>
<tr>
<th>Date</th>
<th>N</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>16/6/09</td>
<td>227</td>
<td>139.5</td>
<td>70</td>
<td>224</td>
<td>25.1</td>
</tr>
<tr>
<td>29/7/09</td>
<td>105</td>
<td>145.6</td>
<td>93</td>
<td>202</td>
<td>21.0</td>
</tr>
<tr>
<td>Total</td>
<td>322</td>
<td>141.4</td>
<td>70</td>
<td>224</td>
<td>24.0</td>
</tr>
</tbody>
</table>

**Table 3.15** Summary of length data for Ardnacrusha juvenile eels 2010 by date sampled

<table>
<thead>
<tr>
<th>Date</th>
<th>N</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>18/06/10</td>
<td>95</td>
<td>76.5</td>
<td>62</td>
<td>142</td>
<td>17.1</td>
</tr>
<tr>
<td>4/08/10</td>
<td>152</td>
<td>74.7</td>
<td>63</td>
<td>164</td>
<td>9.8</td>
</tr>
<tr>
<td>Total</td>
<td>247</td>
<td>75.4</td>
<td>62</td>
<td>164</td>
<td>13.1</td>
</tr>
</tbody>
</table>
Table 3.16 Summary of weight data for Ardnacrusha juvenile eels in 2009 and 2010 by date sampled

<table>
<thead>
<tr>
<th>Date</th>
<th>N</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>16/6/09</td>
<td>227</td>
<td>2.70</td>
<td>0.2</td>
<td>11.6</td>
<td>1.48</td>
</tr>
<tr>
<td>4/8/10</td>
<td>152</td>
<td>0.40</td>
<td>0.2</td>
<td>2.8</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Table 3.17 Summary of condition (K) data for Ardnacrusha juvenile eels in 2009 and 2010 by date sampled

<table>
<thead>
<tr>
<th>Date</th>
<th>N</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>16/6/09</td>
<td>227</td>
<td>0.90</td>
<td>0.49</td>
<td>1.29</td>
<td>0.13</td>
</tr>
<tr>
<td>4/8/10</td>
<td>152</td>
<td>0.81</td>
<td>0.44</td>
<td>1.37</td>
<td>0.16</td>
</tr>
</tbody>
</table>
Table 3.18 Summary of length data for Parteen juvenile eels 2008 by date sampled

<table>
<thead>
<tr>
<th>Date</th>
<th>N</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/6/08</td>
<td>158</td>
<td>156.5</td>
<td>87</td>
<td>298</td>
<td>38.9</td>
</tr>
<tr>
<td>17/6/08</td>
<td>218</td>
<td>146.8</td>
<td>88</td>
<td>255</td>
<td>34.0</td>
</tr>
<tr>
<td>18/6/08</td>
<td>116</td>
<td>153.3</td>
<td>98</td>
<td>236</td>
<td>31.2</td>
</tr>
<tr>
<td>19/6/08</td>
<td>215</td>
<td>150.6</td>
<td>98</td>
<td>318</td>
<td>37.3</td>
</tr>
<tr>
<td>26/6/08</td>
<td>420</td>
<td>153.9</td>
<td>88</td>
<td>275</td>
<td>35.2</td>
</tr>
<tr>
<td>10/7/08</td>
<td>780</td>
<td>142.9</td>
<td>84</td>
<td>267</td>
<td>33.9</td>
</tr>
<tr>
<td>18/7/08</td>
<td>179</td>
<td>177.7</td>
<td>97</td>
<td>291</td>
<td>38.1</td>
</tr>
<tr>
<td>29/7/08</td>
<td>233</td>
<td>157.6</td>
<td>84</td>
<td>292</td>
<td>43.6</td>
</tr>
<tr>
<td>14/8/08</td>
<td>392</td>
<td>138.2</td>
<td>80</td>
<td>310</td>
<td>32.8</td>
</tr>
<tr>
<td>21/8/08</td>
<td>497</td>
<td>155.8</td>
<td>100</td>
<td>315</td>
<td>31.5</td>
</tr>
<tr>
<td>28/8/08</td>
<td>124</td>
<td>162.0</td>
<td>90</td>
<td>329</td>
<td>46.2</td>
</tr>
<tr>
<td>10/9/08</td>
<td>525</td>
<td>189.6</td>
<td>88</td>
<td>300</td>
<td>36.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3857</strong></td>
<td><strong>154.9</strong></td>
<td><strong>80</strong></td>
<td><strong>329</strong></td>
<td><strong>37.9</strong></td>
</tr>
</tbody>
</table>

Table 3.19 Summary of length data for Parteen juvenile eels 2009 by date sampled

<table>
<thead>
<tr>
<th>Date</th>
<th>N</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>26/6/09</td>
<td>102</td>
<td>150.2</td>
<td>89</td>
<td>265</td>
<td>31.0</td>
</tr>
<tr>
<td>10/7/09</td>
<td>473</td>
<td>146.4</td>
<td>76</td>
<td>278</td>
<td>34.1</td>
</tr>
<tr>
<td>28/7/09</td>
<td>114</td>
<td>141.8</td>
<td>88</td>
<td>258</td>
<td>36.7</td>
</tr>
<tr>
<td>29/7/09</td>
<td>30</td>
<td>148.6</td>
<td>83</td>
<td>263</td>
<td>46.0</td>
</tr>
<tr>
<td>14/8/09</td>
<td>38</td>
<td>124.0</td>
<td>89</td>
<td>179</td>
<td>24.0</td>
</tr>
<tr>
<td>17/8/09</td>
<td>43</td>
<td>117.7</td>
<td>93</td>
<td>154</td>
<td>17.8</td>
</tr>
<tr>
<td>18/8/09</td>
<td>12</td>
<td>131.5</td>
<td>100</td>
<td>175</td>
<td>25.3</td>
</tr>
<tr>
<td>20/8/09</td>
<td>19</td>
<td>126.0</td>
<td>97</td>
<td>172</td>
<td>21.9</td>
</tr>
<tr>
<td>21/8/09</td>
<td>38</td>
<td>136.9</td>
<td>84</td>
<td>293</td>
<td>40.6</td>
</tr>
<tr>
<td>26/8/09</td>
<td>22</td>
<td>114.4</td>
<td>86</td>
<td>206</td>
<td>22.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>891</strong></td>
<td><strong>142.1</strong></td>
<td><strong>76</strong></td>
<td><strong>293</strong></td>
<td><strong>34.6</strong></td>
</tr>
</tbody>
</table>
Table 3.20 Summary of length data for Parteen juvenile eels 2010 by date sampled

<table>
<thead>
<tr>
<th>Date</th>
<th>N</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>25/06/10</td>
<td>35</td>
<td>156.9</td>
<td>87</td>
<td>305</td>
<td>40.5</td>
</tr>
<tr>
<td>29/06/10</td>
<td>160</td>
<td>144.3</td>
<td>82</td>
<td>274</td>
<td>40.0</td>
</tr>
<tr>
<td>27/07/10</td>
<td>67</td>
<td>133.7</td>
<td>88</td>
<td>270</td>
<td>45.3</td>
</tr>
<tr>
<td>06/08/10</td>
<td>81</td>
<td>161.4</td>
<td>88</td>
<td>305</td>
<td>49.7</td>
</tr>
<tr>
<td>03/09/10</td>
<td>29</td>
<td>191.5</td>
<td>104</td>
<td>316</td>
<td>54.6</td>
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<tr>
<td>Total</td>
<td>372</td>
<td>151.0</td>
<td>82</td>
<td>316</td>
<td>46.8</td>
</tr>
</tbody>
</table>

Table 3.21 Summary of weight data for Parteen juvenile eels in 2009 and 2010 by date sampled

<table>
<thead>
<tr>
<th>Date</th>
<th>N</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>26/6/09</td>
<td>102</td>
<td>3.8</td>
<td>0.5</td>
<td>16.8</td>
<td>2.9</td>
</tr>
<tr>
<td>20/8/09</td>
<td>19</td>
<td>2.1</td>
<td>0.8</td>
<td>5.8</td>
<td>1.4</td>
</tr>
<tr>
<td>21/8/09</td>
<td>38</td>
<td>3.6</td>
<td>0.5</td>
<td>23.0</td>
<td>4.1</td>
</tr>
<tr>
<td>26/8/09</td>
<td>22</td>
<td>1.7</td>
<td>0.5</td>
<td>10.7</td>
<td>2.0</td>
</tr>
<tr>
<td>29/6/10</td>
<td>160</td>
<td>4.0</td>
<td>0.5</td>
<td>29.0</td>
<td>4.2</td>
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<tr>
<td>3/9/10</td>
<td>29</td>
<td>10.0</td>
<td>1.0</td>
<td>36.0</td>
<td>9.3</td>
</tr>
</tbody>
</table>

Table 3.22 Summary of condition ($K$) data for Parteen juvenile eels in 2009 and 2010 by date sampled

<table>
<thead>
<tr>
<th>Date</th>
<th>N</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>26/6/09</td>
<td>102</td>
<td>0.98</td>
<td>0.47</td>
<td>1.73</td>
<td>0.16</td>
</tr>
<tr>
<td>20/8/09</td>
<td>19</td>
<td>0.93</td>
<td>0.63</td>
<td>1.18</td>
<td>0.18</td>
</tr>
<tr>
<td>21/8/09</td>
<td>38</td>
<td>1.05</td>
<td>0.54</td>
<td>1.51</td>
<td>0.22</td>
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<tr>
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<td>22</td>
<td>0.96</td>
<td>0.63</td>
<td>1.35</td>
<td>0.17</td>
</tr>
<tr>
<td>29/6/10</td>
<td>160</td>
<td>1.00</td>
<td>0.37</td>
<td>1.40</td>
<td>0.17</td>
</tr>
<tr>
<td>3/9/10</td>
<td>29</td>
<td>1.12</td>
<td>0.76</td>
<td>1.54</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Chapter 3

**Table 3.23** Summary of length data for Cathaleen’s Fall juvenile eels 2008 and 2010 by date sampled

<table>
<thead>
<tr>
<th>Date</th>
<th>N</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27/7/08</td>
<td>28</td>
<td>72.1</td>
<td>66</td>
<td>78</td>
<td>3.1</td>
</tr>
<tr>
<td>28/7/08</td>
<td>146</td>
<td>72.5</td>
<td>61</td>
<td>172</td>
<td>14.5</td>
</tr>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12/7/10</td>
<td>124</td>
<td>87.2</td>
<td>54</td>
<td>218</td>
<td>38.7</td>
</tr>
</tbody>
</table>

**Table 3.24** Summary of length data for Inniscarra juvenile eels sampled in 2008, 2009 and 2010

<table>
<thead>
<tr>
<th>Date</th>
<th>N</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14/10/08</td>
<td>17</td>
<td>92.0</td>
<td>78</td>
<td>110</td>
<td>10.2</td>
</tr>
<tr>
<td>2009</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24/7/09</td>
<td>264</td>
<td>133.7</td>
<td>83</td>
<td>199</td>
<td>18.8</td>
</tr>
<tr>
<td>19/8/09</td>
<td>26</td>
<td>129.5</td>
<td>98</td>
<td>157</td>
<td>15.0</td>
</tr>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20/7/10</td>
<td>83</td>
<td>113.6</td>
<td>81</td>
<td>152</td>
<td>16.2</td>
</tr>
</tbody>
</table>
Table 3.25 Mean length according to age group, Ardnacrusha, juvenile eel trap 2008

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>1+</th>
<th>2+</th>
<th>3+</th>
<th>4+</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of eels</td>
<td>10</td>
<td>8</td>
<td>5</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>Mean length (mm)</td>
<td>80.0</td>
<td>117.8</td>
<td>160.6</td>
<td>152.0</td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>16.6</td>
<td>19.4</td>
<td>17.5</td>
<td>16.9</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.26 Mean length according to age group, Parteen juvenile eel trap 2008

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>1+</th>
<th>2+</th>
<th>3+</th>
<th>4+</th>
<th>5+</th>
<th>6+</th>
<th>7+</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of eels</td>
<td>3</td>
<td>15</td>
<td>13</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>Mean length (mm)</td>
<td>91.6</td>
<td>120.8</td>
<td>147.4</td>
<td>147.6</td>
<td>211.5</td>
<td>192.6</td>
<td>180.5</td>
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</tr>
<tr>
<td>SD</td>
<td>11.0</td>
<td>19.6</td>
<td>27.1</td>
<td>29.5</td>
<td>36.3</td>
<td>41.8</td>
<td>12.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.27 Mean length according to age group, Inniscarra juvenile eel trap 2009

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>1+</th>
<th>2+</th>
<th>3+</th>
<th>4+</th>
<th>5+</th>
<th>6+</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of eels</td>
<td>1</td>
<td>3</td>
<td>9</td>
<td>10</td>
<td>1</td>
<td>1</td>
<td>25</td>
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<tr>
<td>Mean length (mm)</td>
<td>96</td>
<td>116.6</td>
<td>136.4</td>
<td>127.6</td>
<td>151</td>
<td>158</td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>-</td>
<td>5.5</td>
<td>9.4</td>
<td>14.6</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
### 3.7 Figures

**Ardnacrusha 2010**

![Graph showing the total catch and cumulative percentage of total catch at Ardnacrusha during 2010.](image)

**Figure 3.2** The total catch (49.732 kg) (bars) of juvenile eels with the cumulative percentage of total catch (line) at Ardnacrusha during 2010.

**Parteen 2008**

![Graph showing the total catch at Parteen in 2008.](image)

**Figure 3.3** The total catch of juvenile eels at Parteen in 2008 (1306 kg).
Figure 3.4 The total catch of juvenile eels at Parteen in 2009 (139 kg)

Figure 3.5 The total catch of juvenile eels at Parteen in 2010 (162 kg)
Figure 3.6 The cumulative percentage of total catch of juvenile eels with month at Parteen during the years 2008–2010

Figure 3.7 Mean monthly water flow in the Kilmastulla River for May–September in 2008, 2009 and 2010
Figure 3.8 The total catch of juvenile eels at Cathaleen’s Fall in 2008 (36 kg)

Figure 3.9 The total catch of juvenile eels at Cathaleen’s Fall in 2009 (85 kg)
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Figure 3.10 The total catch of juvenile eels at Cathaleen’s Fall in 2010 (94 kg)

Figure 3.11 The cumulative percentage of total catch of juvenile eels with month at Cathaleen’s Fall during the years 2008–2010
Figure 3.12 The total catch (23.890 kg) of juvenile eels at Inniscarra in 2009. Data labels indicate the weight (kg) of eels captured.
Figure 3.13 Percentage length frequency distribution for Ardnacrusha eels in 2008 (N = 1200)

Figure 3.14 Changes in mean length (± 95% confidence interval) of eels sampled from Ardnacrusha in 2008. Numbers above the horizontal lines indicate sample sizes
Figure 3.15 Percentage length frequency distribution of eels from Ardnacrusha in 2009 (N = 332)

Figure 3.16 Percentage length frequency distribution of eels from Ardnacrusha in 2010 (N = 247)
Figure 3.17 The length-weight relationship of eels (N = 227) collected at Ardnacrusha in 2009

Figure 3.18 Length-weight relationship of logarithmically transformed values with linear regression equation for eels (N = 227) collected at Ardnacrusha in 2009
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**Figure 3.19** The length-weight relationship of eels (N = 152) collected at Ardnacrusha in 2010

![Length-weight relationship of eels](image1)

\[ W = 4E-07L^{3.1709} \]
\[ R^2 = 0.7153 \]

**Figure 3.20** Length-weight relationship of logarithmically transformed values with linear regression equation for eels (N = 152) collected at Ardnacrusha in 2010

![Logarithmic length-weight relationship](image2)

\[ \text{Log } W = -6.4175 + 3.1709 \text{ Log } L \]
\[ R^2 = 0.7153 \]
Figure 3.21 Percentage length frequency distribution of juvenile eels from Parteen in 2008 (N = 3857)

Figure 3.22 Changes in mean length (± 95% confidence interval) of eels sampled from Parteen in 2008. Numbers above the horizontal lines indicate sample sizes
Figure 3.23 Percentage length frequency distribution of juvenile eels from Parteen in 2009 (N = 891)

Figure 3.24 Changes in mean length (± 95% confidence interval) of eels sampled from Parteen in 2009. Numbers above the horizontal lines indicate sample sizes
Figure 3.25 Percentage length frequency distribution of juvenile eels from Parteen in 2010 (N = 372)

Figure 3.26 Changes in mean length (± 95% confidence interval) of eels sampled from Parteen in 2010. Numbers above the horizontal lines indicate sample sizes
Chapter 3

**Figure 3.27** The length-weight relationship of eels (N = 181) pooled from four samples collected at Parteen in 2009

**Figure 3.28** The length-weight relationship of logarithmically transformed values with linear regression equation for eels (N = 181) pooled from four samples collected at Parteen in 2009
Figure 3.29 The length-weight relationship of eels (N = 189) pooled from two samples collected at Parteen in 2010

Figure 3.30 The length-weight relationship of logarithmically transformed values with linear regression equation for eels (N = 189) pooled from two samples collected at Parteen in 2010
Figure 3.31 Percentage length frequency distribution of juvenile eels from Cathaleen’s Fall in 2008 (N = 174)

Figure 3.32 Percentage length frequency distribution of juvenile eels from Cathaleen’s Fall in 2010 (N = 124)
Figure 3.33 Percentage length frequency distribution of juvenile eels from Inniscarra in 2008 (N = 17)

Figure 3.34 Percentage length frequency distribution juvenile eels from Inniscarra in 2009 (N = 264)
Figure 3.35 Percentage length frequency distribution of juvenile eels from Inniscarra in 2010 (N = 83)
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Figure 3.37 The mean ± SD total length ($L_T$) eels trapped at Parteen against river year classes (N = 50). Numbers above each point indicate the total number of individuals in each year class.
Figure 3.38 The mean ± SD total length ($L_T$) eels trapped at Inniscarra against river year classes (N = 25). Numbers above each point indicate the total number of individuals in each year class.
Plate 3.1 Ardnacrusha hydroelectric power station (HPS) on the River Shannon with the location of the juvenile eel trap indicated with a red arrow (a). View of the trap set up taken from the top of the Borland lift (b). The concrete ramp covered with Tensar® Mat and the holding tank (c)
Plate 3.2 The Parteen regulating weir on the River Shannon where water is diverted to Ardnacrusha HPS via the headrace canal. A red arrow indicates the location of the juvenile eel trap (a). View of the Parteen trap (indicated with red arrow) from the northern bank of the old river channel (b). The holding tank and ramp extending to the base of the pool and traverse fish pass (c)
Plate 3.3 Cathaleen’s Fall HPS on the River Erne with the locations of the juvenile eel traps indicated by the red arrows
Plate 3.4 Inniscarra HPS on the River Lee (a). The red arrow indicates the location of the juvenile eel trap holding tank (b) and ramp (c)
Chapter 4 Environmental factors influencing the upstream migration of juvenile eels on the River Shannon

4.1 Introduction

Once anguillid leptocephalus larvae complete their oceanic migration and reach the continental shelf they metamorphose into glass eels and migrate inshore to coastal waters and estuaries where they become pigmented elvers (Tesch, 2003). Eels display facultative catadromy (Tsukamoto et al., 1998; Tzeng et al., 2000; Tsukamoto and Arai, 2001; Jessop et al., 2002; Arai et al., 2006) with some glass eels and elvers staying in coastal waters while others progress up rivers and streams to complete the growth phase of their lifecycle in freshwater habitat. The reasons for these different migratory tactics are poorly understood. Edeline et al. (2006) carried out experimental tests to study the effects of changes in water temperature and body condition on locomotor activity (upstream swimming) and salinity preference of Anguilla anguilla glass eels. They concluded that water temperature and glass eel energetic status are key proximate factors for the control of the facultative catadromy in the eel.

Tendencies to migrate after glass eel stage varies greatly both between individual eels and with time (White and Knights, 1997b). In experiments on elver and yellow stage Anguilla anguilla carried out by Imbert et al. (2008) both inter- and intra-stage locomotor behaviour plasticity was observed. Measurements of morphometric characters and thyroid hormones in individuals of both eel stages suggested that upstream migration was related to good physiological condition in elvers and to stress conditions in yellow eels (Imbert et al., 2008).

The number of migrant eels which colonise freshwater also varies greatly between years (Feunteun et al., 2003) and could be related to the density dependent (i.e. the number of glass eels and elvers in estuaries and the number of older fish in the lower reaches of the
river) as well as density independent factors such as environmental conditions (Acou et al., 2009). Naismith and Knights (1988) proposed that the variable timing of migrations from year to year suggest it is environmental conditions affecting the transition from brackish to freshwater, rather than the total elver supply that cause recruitment variability.

Eels have a highly developed olfactory sense and this has lead to the assumption that they use their olfactory organs to locate different habitats and in the case of glass eels to orientate to freshwater flowing into the sea (Tesch, 2003). The role of eel odour as an attractant for migrating glass and yellow stage eels was assessed in a field experiment undertaken by Briand et al. (2002) using an eel ladder trap and the presence of conspecific odour was found to coincide with increased catches of eels. Sorensen (1986) found that Anguilla rostrata elvers were attracted to the odor of decaying leaf detritus and migrating alewives (Alosa pseudoharengus) but that conspecific odours were only weakly attractive. Tosi and Sola (1993) suggested that geosmin, an odorant typical of inland water produced by actinomycetes, could be an important inland water marker involved in the orientation of glass eels towards freshwater and Creutzberg (1961) found that migratory elvers strongly preferred stream water to both estuarine and well water.

An array of environmental factors have been proposed as being stimuli for either initiating, maintaining or inhibiting upstream migration of juvenile eels and many investigations have been undertaken to discern their effect. However, clear cause and effect relationships can be difficult to identify because multiple environmental factors may act in unison on the migration and the importance of these variables may vary with time and local hydrological and climatic conditions (Sorensen and Bianchini, 1986; White and Knights, 1997b). Lower eel densities observed with increased distance inland from the ocean contributes to the difficulty in assessing the impacts of
environmental variables on upstream migration (White and Knights, 1997b; Ibbotson et al., 2002; Laffaille et al., 2005).

The effect that changes in water salinity have on glass eel and elvers’ rheotactic response has been investigated by Miles (1968) and Edeline et al. (2006). The relationship between tidal stage and the upstream eel migration has been shown for European eel Anguilla anguilla (Deelder, 1958; Creutzberg, 1961; Crivelli et al., 2008; Prouzet et al., 2009), American eel A. rostrata (McCleave and Kleckner, 1982; Martin, 1995) and Japanese eel A. japonica (Tzeng, 1985) glass eel and elvers. The influence of rainfall and river flow on elver migration has been studied by a number of authors including Jellyman and Ryan (1983), Sorensen and Bianchini (1986) and Domingos (1992).

Peaks in Anguilla spp. activity have been found to correspond with lunar phases, which affects both nighttime light regimes and tidal amplitudes (Cairns and Hooley, 2003). Varying strengths of relationship have been observed for Anguilla spp. glass eel and elver activity and lunar phase (Tzeng, 1985; Tesch, 2003; Zhang et al., 2008; Jellyman et al., 2009; Sullivan et al., 2009).

Day length is suggested as a factor that may contribute to the initiation or control of upstream migration in Anguilla australis (Sloane, 1984) and in salmonids it is known that increasing day length in spring is a factor involved in triggering smoltification (Hoar, 1988). In eels, the effect of photoperiod variation on the physiology and behaviour of eels is relatively unexplored (Edeline et al., 2009).

Water temperature is among the most frequently observed environmental factors influencing upstream migration of glass eels, elvers and larger juvenile eels of Anguilla
Chapter 4

*anguilla* (Tosi *et al.*, 1990; White and Knights, 1997b; Tesch, 2003; Edeline *et al.*, 2006; Acou *et al.*, 2009), *Anguilla rostrata* (Sorensen and Bianchini, 1986; Haro and Krueger, 1988; Martin, 1995; Verdon *et al.*, 2003; Sullivan *et al.*, 2006; Hammond and Welsh, 2009) and glass eels of *Anguilla* spp. in New Zealand (Jellyman and Lambert, 2003; August and Hicks, 2008) and in Australia (McKinnon and Gooley, 1998) and for *Anguilla japonica* (Tzeng, 1985; Chen *et al.*, 1994)

The main aim of this study was to examine the influence of environmental factors on the variation in eel recruitment in the River Shannon at the Parteen regulating weir and to develop a predictive model to enable more focused efforts of eel collection for stocking the river catchment upstream of the weir.
4.2 Study area

A detailed description of the study area is provided in Chapter 2. Juvenile eel trapping took place directly downstream of the Parteen regulating weir adjacent to the entrance of the pool and traverse fish pass (Figure 4.1 and Figure 4.2). The trap used at the Parteen regulating weir is based on a design by O’Leary (1971) which is described in more detail in Chapter 3.
Figure 4.1 Map of the Lough Derg and the lower River Shannon showing the location of the Parteen regulating weir

Figure 4.2 Location of the juvenile eel trapping site on the lower River Shannon at the Parteen regulating weir
4.3 Materials and methods

4.3.1 Catch Data
Comprehensive surveys of the Parteen juvenile eel trap took place over 3 upstream migration seasons, from 2008–2010. Traps were inspected once every three days on average and more frequently during migration peaks. The analyses of juvenile eel catch data at Parteen involved standardisation of catches per day (excluding the first day’s recorded catch, which represented the cumulative catch for a variable number of preceding days).

4.3.2 Environmental Data
Cumulative daily rainfall and mean daily air temperature recorded at Shannon airport was obtained from the Met Éireann, the Irish National Meteorological Service. Water temperature was recorded on a daily basis at Parteen and using a TidbiT v2 temperature data logger (Onset Computer Corporation, Pocasset, MA, USA). Data for percentage moon fullness and day length was obtained from the United States Naval Observatory, http://www.usno.navy.mil/USNO. Percent moon fullness was quantified as a range from 0 to 1; new moon (0.00), first and last quarter (0.50), and full moon (1.00). The water discharge from the Parteen reservoir into the lower River Shannon was maintained at the statutory minimum flow rate of 10 m$^3$ s$^{-1}$ throughout the period of operation of the juvenile eel trap at Parteen in the years 2008, 2009 and 2010. The flow in the lower river is, however, influenced by a number of tributaries, particularly the Kilmastulla River (Moriarty, 1986) and water flow and water level data for the Kilmastulla River was obtained from the Environmental Protection Agency (http://hydronet.epa.ie/hydronet.html) and used as a proxy for water flow and level changes in the lower River Shannon. Measurements are recorded by data loggers at 15 minute intervals and daily mean values were used for analysis.

4.3.3 Data Analyses
Catch and environmental data were analysed using IBM SPSS Statistics 18 (SPSS Inc., Chicago, IL). Because of the complexities involved in analysing time series collected at
unequal time intervals, it was decided to convert the series into one with equal time intervals. This was achieved by averaging the first seven observations, then the next seven, and so on. The series analysed was then $y_i, i = 1, 2, \ldots, 51$, consisting of these 51 averages.

The potential list of input variables that were considered when forming a predictive model for the dependent variable, catch, were as follows; rainfall, water flow, water temperature, air temperature, percentage moon fullness and year. All of these variables are quantitative, except the last one, year, which was treated as a qualitative variable. This variable, year, which is at three levels, 2008, 2009 and 2010, was treated as a random effect (which means that one views the three years as a sample from a whole population of years about which one would like to make inferences in the sense of the effect of time on catch). It transpired that whether year was treated as a fixed or as a random effect made no difference in so far as inferences about the other predictors in the model were concerned (that is, the $p$-value for the effect of any given predictor in the model was essentially the same whether or not year was fixed or random).

There tends to be correlation between observations of catch taken at different time points. Typically there is at least first-order autocorrelation, that is, correlation between $y_t$ and $y_{t-1}$ (this is evident by the magnitude of the first-order sample autocorrelation). For such series, one cannot apply standard regression or analysis of variance (ANOVA) methods without either first transforming the response variable to one for which standard regression analysis is appropriate (in the sense that the assumptions underlying the usual linear regression model hold, including lack of correlation between the response values at the various combinations of values of the input variables), or by using alternative analysis. Such alternative analyses include the use of time series models (J. Sheahan, pers. comm.).
The aim of transforming the original data is often to attempt to eliminate statistically significant autocorrelation (Fox et al., 2000; Bonhommeau et al., 2008b) and possibly also other potential problems like heterogeneity of variances (of the response variable at the various combinations of values of the input variables), non-normality of the response variable (at each combination of values of the inputs) and even non-linearity of the model relating the response variable to the input variables. Common transformations of the response variable are natural log and square root transformation. In time series-type data, where autocorrelation is present transformation is usually performed by taking differences of some order, for example, first-order differencing: $y_t - y_{t-1}$, (Thompson and Page, 1989) is used where there is first-order autocorrelation and one then proceeds to model the new series $u_t = y_t - y_{t-1}$, provided that it is stationary, i.e. that the mean, variance and autocorrelation structure are constant or do not fluctuate periodically over time.

Appropriate statistical fitted models are ones which explain well the systematic variation in the data and that give residuals that reflect pure randomness (“residuals” are the differences between the observed values and those predicted or fitted by a model) (Thompson and Page, 1989; Bonhommeau et al., 2008b). Irrespective of what model that was fitted to the series $y_i$, $i = 1,2,\ldots,51$, the plot of the residuals from the model displayed an obvious downward trend, whereas - as indicated - an acceptable model must have a residual plot in which the following patterns do not occur to a statistically significant extent: trend (upward, downward or curvilinear), heterogeneity of variances, significant correlations between values (e.g. large values tending to be followed by smaller values, etc.), or violation of approximate normality of the error distributions in the underlying model (Zar, 1999). Accordingly, it was required to take the differences $u_t = y_t - y_{t-1}$, and to find a model for these differences. In practice, this means that the model used ends up predicting the differences of the original averaged series rather than predicting values of the series itself (although it is possible to recover one from the other).
In the present analysis in which there are both covariates (quantitative input variables) and factors (qualitative input variables) one may use the general linear model (GLM) procedure available in SPSS. However, much of the analysis was carried out using indicator variables for the qualitative variable (year) and for convenience a multiple regression procedure (backward elimination) in the same program was used as the output available from the regression procedure provides certain results on request that are not routinely provided using GLM. This includes multicollinearity diagnostics, such as the variance inflation factors (VIF).
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4.4 Results

High rainfall and river flow measurements were recorded in 2008 owing to exceptionally high rainfall that occurred in August 2008. On August 6th 38 mm of rain was recorded over a 60 minute period, the highest hourly rainfall ever recorded for any month at a synoptic station in Ireland (Met Éireann, 2008). Rainfall and river flow recorded in 2010 were significantly lower than in 2009 (Mann-Whitney U-test, rainfall: $p < 0.001$; flow: $p = 0.01$). The mean water temperature recorded in 2008 sampling period was lower than in the other two years and the range of water temperature experienced was higher owing to the longer sampling period in 2008 which started in May and ended in October (Table 4.1). The sampling periods of 2009 and 2010 were relatively similar to each other in respect water temperature and had a smaller temperature range than that of 2008 (Table 4.2). Over the three years 2008 to 2010 80.9% of the catch was made when water temperatures were between 16 and 18º C (Figure 4.3).

A peak in the eel catch in August 2008 coincided with a peak in river flow resulting from the high rainfall experienced in the preceding days (Figure 4.4). 63% of the total catch in 2008 was recorded in August. In July 2010 a less pronounced increase in eel catch coincided with a peak in river flow (Figure 4.6). Peaks in eel catch were generally absent during full moon periods (Figure 4.7 to Figure 4.9).

The multiple regression model indicated that moon fullness, day length, year, flow and water temperature accounted for 34% of the variation in the difference in average eel catch values (Table 4.2). The percentage variation accounted for by each regression parameter in the model is given in Table 4.2. Day length and flow were positively related to the difference in average catch and accounted for 9% and 8% of the total variation respectively. The remaining variables, moon fullness, year and water temperature had negative regression coefficient values and accounted for smaller percentage change in the total variation.
In an attempt to improve the predictive power of the model the analysis was repeated without the inclusion of two exceptionally high catch values recorded in August 2008. The model generated had a similar $R^2$ value (0.33) to the original model (0.34) and each of the predictor variables present in the original model were present in the same order of importance.

**Table 4.1** Mean, standard error (SE) and range of environmental variables for 3 sampling periods of a study of upstream migration at the Parteen juvenile eel trap

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>SE</th>
<th>Range</th>
<th>Mean</th>
<th>SE</th>
<th>Range</th>
<th>Mean</th>
<th>SE</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>River flow (m$^3$s$^{-1}$)</td>
<td>2.55</td>
<td>0.17</td>
<td>10.03</td>
<td>1.43</td>
<td>0.10</td>
<td>5.06</td>
<td>0.69</td>
<td>0.05</td>
<td>2.48</td>
</tr>
<tr>
<td>Rainfall (mm)</td>
<td>3.73</td>
<td>0.49</td>
<td>52.5</td>
<td>3.62</td>
<td>0.48</td>
<td>22.3</td>
<td>2.14</td>
<td>0.37</td>
<td>15.70</td>
</tr>
<tr>
<td>Water temperature (º C)</td>
<td>15.48</td>
<td>0.13</td>
<td>8.67</td>
<td>17.36</td>
<td>0.09</td>
<td>3.76</td>
<td>18.15</td>
<td>0.08</td>
<td>3.40</td>
</tr>
</tbody>
</table>

**Table 4.2** Multiple regression analysis of factors influencing the difference in average catch of juvenile eels; $N = 48$, $F = 4.58$, $p = 0.002$

<table>
<thead>
<tr>
<th>Effect</th>
<th>B</th>
<th>SE</th>
<th>$\beta$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-0.66</td>
<td>2.59</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Moon fullness (%)</td>
<td>0.53</td>
<td>0.15</td>
<td>-0.365</td>
<td>0.001</td>
</tr>
<tr>
<td>Day length (hours)</td>
<td>-1.69</td>
<td>0.57</td>
<td>0.713</td>
<td>0.005</td>
</tr>
<tr>
<td>Year</td>
<td>-0.45</td>
<td>0.20</td>
<td>-0.395</td>
<td>0.031</td>
</tr>
<tr>
<td>Flow (m$^3$s$^{-1}$)</td>
<td>0.54</td>
<td>0.17</td>
<td>0.63</td>
<td>0.003</td>
</tr>
<tr>
<td>Water temperature (º C)</td>
<td>-0.71</td>
<td>0.31</td>
<td>-0.492</td>
<td>0.027</td>
</tr>
</tbody>
</table>

$R^2$ is the standardised regression coefficient (percentage of total variance explained by that predictor in parentheses). The sum of the percentage of total explained variances equals the $R^2$. 

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Figure 4.3 Frequency distribution of 7 day average juvenile eel catch (%) recorded at different water temperature classes at Parteen during the 2008, 2009 and 2010 migratory period (N = 51)

Figure 4.4 The 7 day average variation in Parteen juvenile eel percentage catch and water temperature and flow rate during 2008
Figure 4.5 The 7 day average variation in Parteen juvenile eel percentage catch and water temperature and flow rate during 2009

Figure 4.6 The 7 day average variation in Parteen juvenile eel percentage catch and water temperature and flow rate during 2010
Figure 4.7 The 7 day average variation in Parteen juvenile eel percentage catch and percentage moon fullness during 2008

Figure 4.8 The 7 day average variation in Parteen juvenile eel percentage catch and the percentage moon fullness during 2009
Figure 4.9 The 7 day average variation in Parteen juvenile eel percentage catch and the percentage moon fullness during 2010
4.5 Discussion

Juvenile eel pass traps are considered to provide accurate estimates of the relative number of migrant eels, their year-to-year variability and migration timing (Acou et al., 2009). Clear relationships between environmental factors and juvenile eel migration are difficult to determine because environmental factors may act in concert on the migration and may vary with time and local climatic and hydrological activities (White and Knights, 1997b). In the present study parameters that explained a statistically significant portion of the variation in difference in juvenile eel catch at Parteen were, in order of importance: day length, flow, water temperature, moon fullness and year.

Increasing day length had a positive influence on the variation in the Parteen juvenile eel catch (Table 4.2). This finding is in agreement with propositions that the increasing day length of summer is a seasonal cue that may contribute to the initiation and control of migration in juvenile eels (Jellyman, 1977; Sloane, 1984). Vøllestad et al.(1986) found that day length was the main factor explaining variation in the duration of the migration of silver eels and it was also the main factor in explaining migratory speed (Vøllestad et al., 1994). Julian days, (or more specifically, day of the year, ranging from 1 to 366), used as a proxy for photoperiod by Durif and Elie (2008) was shown to be significantly correlated with migration of silver eels. Durif et al. (2008) suggested that photoperiod activates migration through the silversing process and that eels may rely on seasonal cues to synchronise puberty so that the future spawners will be physiologically ready for migration at the same time.

Flow was found to have a positive influence on catches on juvenile eels at Parteen and this result is in agreement with the findings of Jellyman and Ryan (1983) who monitored the migration of elvers and juvenile eels (Anguilla australis and Anguilla dieffenbachia) in Lake Pounui, New Zealand and revealed that water level had a significant influence on both the periodicity and size of the migration, with peak catches observed several days after peaks in water level following a flood, except during low temperatures. Chen
et al. (1994) also found a significant positive relationship between *Anguilla japonica* elver catches and rainfall with peaks in elver catches coinciding with peaks in rainfall. At Parteen the most apparent evidence of the positive influence of river flow on the magnitude of the juvenile eel catch was in August 2008 (Figure 4.4) when an exceptional peak in catch coincided with unusually high flow in the Kilmastulla River. Moriarty (1986) reported a similar finding from his study of juvenile eels at Parteen where more than half of the total catch in 1980 was made in a two week period in August when the flow rate on the Kilmastulla River was more than three times the monthly average (see Chapter 3).

Acou *et al.* (2009) carried out short time-scale analyses of environmental factors (river discharge and water temperature) and recruitment of juvenile eels (*Anguilla anguilla*) captured in a pass traps in a small coastal catchment, the Frémur River, in north-west France, but found that catch data were poorly explained on a daily, weekly and monthly basis. They then focused on an annual analysis of environmental factors and recruitment and found that annual recruitment was related to the mean river discharge recorded during the first month that preceded the migration peak of the year. In analysis of *Anguilla rostrata* glass eel recruitment data for two estuaries on the east coast of the United States covering a period of 16 and 18 years, Sullivan *et al.* (2006) found that above average glass eel abundance was positively correlated with higher than average winter precipitation. The volume and timing of river discharge are dependent on the size of the catchment and the channel flow characteristics and Acou *et al.* (2009) suggested that discharge may provide information to anguillid eels about the amount of habitat available and its accessibility or that the relationship between flow and juvenile eel catches may be due to olfactory cues that accompanied the increase in river flow.

In contrast to the findings in the present study, Sloane (1984) found a significant negative relationship between juvenile eel (*Anguilla australis*) catches and water discharge at a power station outfall in Tasmania. However, the circumstances at the
Parteen regulating weir differ as increased discharge in the lower River Shannon during the juvenile eel migration period is generally the result of increased discharge from its tributaries not spillage from the weir. In addition to this, the lower River Shannon below the Parteen regulating weir retains the character of a natural river with many riffle and pool sections as well as islands, and increased discharge would not be the impediment to upriver migrating eels that it would be in a power station tailrace, as eels could use areas of low flow speed outside of the main current. According to experimental research undertaken by McCleave (1980), elvers would be able to make virtually no progress against water currents > 50 cm s\(^{-1}\) and that migration in freshwater involved avoidance of free stream speeds and a combination of burst and sustained swimming.

Water temperature was negatively related to the difference in eel catches and explained just 6% of the variation in the regression model. Over the three years examined the majority of catch was recorded when water temperature range from 16 to 17º C (Figure 4.3). Variation in water temperature above 10–12º C was shown to have little effect on elver movement in the case of *Anguilla rostrata* (Sorensen and Bianchini, 1986) elvers and *Anguilla* spp. elvers in New Zealand (Jellyman and Ryan, 1983) cited by Jessop (2003b). Sorensen and Bianchini (1986) found that although it appeared that migration of *Anguilla rostrata* elvers at the mouth of a Rhode Island stream required water temperature to exceed a threshold of 10–15 ºC water temperature had little if any influence once this threshold was exceeded. Similarly Martin (1995) observed that river water temperature only had a significant influence on catches of *Anguilla rostrata* elvers at the start and near the end of the migration. In a study of migrating juvenile eels, *Anguilla anguilla* on the Rivers Severn and Avon in England, White and Knights (1997b) found that the key stimulus for migration of elvers and older juvenile eels at the tidal limit was water temperature and there were some weaker monthly influences related to seasonal temperature increases. The effect of temperature was weakened with distance upstream and it was suggested that this correlates with the increasing proportion of older and larger eels in the catches with distance from the estuary and
these larger eels being less sensitive to temperature. At Parteen a similar set of circumstances occur, with the trap located approximately 15 km from the tidal limit and the catch is dominated by juvenile eels > 100 mm $L_T$.

Percentage moon fullness and juvenile eel catch displayed a significant negative relationship but percentage moon fullness explained only 5% of the variation in catch. Peaks in eel catch were generally absent around the full moon phase but no consistent pattern was apparent (Figure 4.7 to Figure 4.9). Sullivan et al. (2006) also found that lunar phase was a moderate to weak environmental factor affecting *Anguilla rostrata* glass eel abundance. Tzeng (1985) found that catches of *Anguilla japonica* elvers in the coastal waters of Northern Taiwan followed the lunar cycle, with peak catches occurring around the time of the new moon and were absent during full moon periods indicating that moonlight was a determining factor in the lunar periodicity of elver migration. Elver activity in rivers followed a semi-lunar rhythm however, with peak catches occurring around the full and new moon. Anguillid elvers use tidal movements to progress further upriver (Creutzberg, 1961) and Tzeng (1985) observed that the increased amplitude of spring tides initiated the migration of elvers and that peaks in migration activity occurred 2–3 days after new and full moons which coincides with the age of the tide.

Jellyman (1977) did not find any direct effect of the lunar cycle on elver migration on the Waikato River in New Zealand where the arrival times of elver was consistent each year. In a later study on factors affecting glass eel recruitment on the Grey River in New Zealand, Jellyman and Lambert (2003) observed that moon phase, expressed through tides and moonlight, was an important factor, with reduced likelihood of migration during the full moon.
High interannual variation at Parteen in the catch of migrating juvenile eels was observed in this study and explains the occurrence of year as a significant factor in the regression model. This interannual variability in recruitment has been reported by other authors for *Anguilla* spp. including Acou *et al.* (2009), White and Knights (1997b), Vøllestad and Jonsonn (1988) and Sullivan *et al.* (2009). Bonhommeau *et al.* (2008b) analysed short term interannual variability in recruitment of glass eels (*Anguilla anguilla*) for the years 1994–2004 and long term trends for the period 1960–2002 and revealed a negative correlation between glass eel recruitment and primary production in the Sargasso Sea supporting the hypothesis that variability in recruitment is linked to food availability and/or composition in the Sargasso Sea through the control of leptocephali survival and growth.

Acou *et al.* (2009) suggested that inter annual variability in riverine recruitment is due to interactions between density-dependent (i.e. number of *A. anguilla* glass eels and elvers in the estuary and the downstream parts of the river) and density-independent (i.e. environmental variables) factors. Intraspecific competition and agnostic behaviour were seen to increase among juvenile eels with increasing population density and biomass in experiments undertaken by Knights (1987) and with water temperature (Nyman, 1972) and it has been proposed that this could encourage dispersal and upstream migration (White and Knights, 1997b).

Sorenson and Bianchini (1986) failed to discern any environmental variable with a strong influence on migration of elvers of the American eel, *Anguilla rostrata*, in freshwater in a study carried out in a Rhode Island stream. They concluded that freshwater migration of elvers appears to be influenced by several environmental variables and that the relative importance of these is determined by local hydrographic conditions and behavioural changes occurring in elvers at the interface of fresh and salt water. They also proposed that it is unlikely that freshwater migration is directly influenced by the absolute values of environmental variables and instead daily or weekly
trends and relative fluctuations in these variables would seem more likely to influence migrational activity. Similarly, in the present study a relatively small but statistically significant amount of the variation in juvenile eel catch at Parteen was explained by a number of environmental variables.

Much effort has been dedicated to identifying which of several environment factors trigger the migration of fish, particularly migration of freshwater and anadromous salmonids (Lucas et al., 2001). Single factors such as high river flow events, tidal amplitude, water temperature variation etc. have been proposed as being the most significant influence on migration or it has been suggested that these different factors may act in concert (White and Knights, 1997b) and may be influenced by local hydrographic conditions (Sorensen and Bianchini, 1986). An alternative interpretation of the effect of environmental stimuli was proposed by Ovidio et al. (1998) who suggested that the migration was triggered by environmental unpredictability and would start when the forces promoting residency are outweighed by those stimulating the fish to move.
Chapter 5 *Anguillicoloides crassus* infection in juvenile eels

5.1 Introduction

*Anguillicoloides crassus,* formerly known as *Anguillocola crassus* (Kuwahara et al. 1974) is a parasitic Dracunculoid nematode and a natural parasite of the Japanese eel *Anguilla japonica.* It was most likely introduced to Europe in the late 1970s or early 1980s through the uncontrolled intercontinental transfer of live eels from East Asia or New Zealand. It was first reported as a parasite of *Anguilla anguilla* in Europe in 1982 (Neumann, 1985) and it spread rapidly throughout Northern Europe (Peters and Hartmann, 1986; Koie, 1991).

It is an aggressive coloniser (Ashworth and Blanc, 1997) and the successful expansion of its range is due to a combination of human assisted dispersion of the final host, the efficient dispersion mechanisms of the parasite itself and the ability of the hatched larvae to survive a wide range of pH, temperature and salinity gradients (Kennedy and Fitch, 1990). It has a wide variety of intermediate and paratenic hosts including cyclopoid copepods, amphibian larvae and aquatic insect larvae (de Charleroy et al., 1990; Moravec and Skoráková, 1998). It is able to infect eels of all sizes (de Charleroy et al., 1990) including glass eels which can be readily infected with *Anguillicoloides* by feeding on the copepods, the intermediate host (Nimeth et al., 2000).

The first record of the nonindigenous swimbladder inhabiting nematode *Anguillicoloides crassus* in Ireland was from eels captured in 1997 in the Waterford estuary (McCarthy et al., 1999). From preliminary analysis of information on the presence of *Anguillicoloides* in all catchments in the Republic of Ireland and four Northern Ireland catchments which are included in this quantification in support of a transboundary management plan, it is now estimated that the parasite may have spread to as much as 73% of the wetted area, which is equivalent to 75% of the potential eel
production (Anon., 2008a). The spread of *Anguillicoloides* has been facilitated by a number of factors and intra- and inter-catchment movement of eels for stocking has been partly responsible for the speed of this process (Belpaire *et al.*, 1989; Kirk, 2003). *Anguillicoloides* infection in glass eels has been shown to cause severe histological changes to the swimbladder wall (Nimeth *et al.*, 2000). In elvers it has been observed that the impact of infection on the swimbladder was dilation of blood vessels, inflammation, and rupture. In eels surviving these acute stages the swimbladder had fibrotic walls and in some instances showed adhesion to the surrounding organs (van Banning and Haenen, 1990) cited by Kirk (2003). Such severe pathological damage to the swimbladder most likely reduces its ability to function (Nimeth *et al.*, 2000).

Under the EC Regulation (2007) and its associated guidelines the collection of data on the disease status of eels of each life stage is required in order to identify areas producing high-quality spawners (i.e. with low parasite burdens) and to maximise protection for these areas (Belpaire *et al.*, 2011).

In this study juvenile eels from the Shannon, Erne and Lee river systems were examined for the presence of *Anguillicoloides crassus*. Where infection by *Anguillicoloides* was observed details of the prevalence and infection intensity were determined. Relationships between eel length and condition and the infection intensity were also examined.
5.2 Materials and methods

Samples (N = 498) were taken at irregular intervals from the Parteen and Ardnacrusha juvenile eel traps during the 2008, 2009 and 2010 migratory period. More intensive sampling was carried out during periods of high catch. On the River Lee samples (N = 73) were collected in October 2008, July 2009 and September 2010. On the River Erne one sample (N = 44) was collected in July 2010.

Eels were euthanised on the day of sampling using a 1:10 solution of clove oil dissolved in ethanol (70%). An overdose (5 ml) of this solution was added to a 10 l water bath in which the eels were immersed. The eels were maintained in the anesthetic solution for 5–10 minutes after cessation of opercular movement to ensure they had expired (Neiffer and Stamper, 2009). The eels were frozen immediately after being removed from the water bath. Frozen eels were fully thawed and excess water was removed using blotting paper prior to examination in the laboratory. They were measured [total length (LT) to the nearest mm] and weighed (to the nearest 0.1 g).

Fulton’s Condition Factor (K) was calculated as follows:

\[ K = 10^3 \times \frac{W}{L^3} \]

Where W is weight in grams and L is length in centimeters. This factor compares the weight of a fish with that expected from an isometric weight-length relationship and can be used to compare condition of fish within and between populations. Fish that are heavier than average for a particular length are considered to be in better condition (Anderson and Neuman, 1996). The swimbladder was removed and opened. Anguillicoloides present in the swimbladder lumen were removed, counted and the number of adult and larvae determined under a binocular microscope. The swimbladder was then placed between two glass slides and examined under a binocular microscope to determine the presence of larvae in the swimbladder wall (Gollock et al., 2004).
Differences in total length, body weight, and condition factor among eel groups were tested using the Mann-Whitney $U$-test (M-W $U$) for 2 samples and the non-parametric Analysis of Variance Kruskal-Wallis test (Kruskal-Wallis ANOVA) test for 3 or more samples. Parasitological population descriptors were used in accordance with Bush et al. (1997). Prevalence and mean intensity were calculated using the following formulae:

$$\text{Prevalence} = \left( \frac{\text{No. of infected eels in sample}}{\text{Total No. of eels in sample}} \right) \times 100$$

$$\text{Mean Intensity} = \left( \frac{\text{Total No. of Anguillicoloides}}{\text{Total No. of infected eels in sample}} \right)$$

Intensity (of infection) is the number of parasites in a single infected eel. Parasite abundance is the number of parasites in a single host regardless of whether or not the host is infected.

Data was analysed using IBM SPSS Statistics 18 (SPSS Inc, Chicago, IL). Significance was accepted at $p < 0.05$. Differences in prevalence between years were tested with Pearson’s $\chi^2$ test. The frequency distributions of intensity (of infection) were compared using the Kruskal-Wallis test and the Mann-Whitney $U$-test. This comparison indicates whether the levels of infection tend to be different between infected hosts of the samples (Rózsa et al., 2000).

An index of the degree of dispersion of Anguillicoloides among individual eel hosts was provided by calculating the variance to mean ratio ($s^2/\bar{x}$) of the parasite abundance. For overdispersed distributions the ratio is greater than $> 1$, for random distributions it is about $= 1$ and for underdispersed distributions it is $< 1$ (Anderson and Gordon, 1982).
The exponent \((k)\) of the negative binomial distribution and the estimate of the arithmetic mean \((\mu)\) was determined according to the method described by Fowler et al. (1998). The goodness of fit between observed and expected frequencies (negative binomial) was evaluated by Pearson’s \(\chi^2\) test.
5.3 Results

5.3.1 Ardnacrusha

Descriptive statistics for length, weight and condition of eels collected are shown in Table 5.1. The length of the eels examined ranged from 62–192 mm and the mean length was 104 mm. This size range is typical of eels utilising the Ardnacrusha juvenile trap where eel length recorded from unbiased samples ranged from 60–224 mm in the years 2008–2010.

Details of infection levels of Anguillicoloides recorded in eels sampled in the years 2008–2010 are expressed as prevalence, mean intensity and maximum parasite burden in Table 5.2. The highest prevalence was recorded in a sample collected in 2008 (70%) and the mean prevalence for 2008 (66%) was higher than mean prevalence recorded in other years. There was a significant difference in prevalence ($\chi^2 = 38.3$, d.f. = 2, $p < 0.001$) and intensity (Kruskal-Wallis ANOVA, $p < 0.001$) recorded between years. Mean intensity of infection in the samples examined ranged from 1.00 to 2.10 and the maximum parasite burden ranged from 1 to 6.

There was a significant difference in intensity between samples in 2008 (Kruskal-Wallis ANOVA, $p < 0.01$) while no significant difference in intensity occurred between samples examined within the years 2009 (M-W U, $p > 0.05$) or 2010 (M-W U, $p > 0.05$).

The variance to mean ratio ($s^2/\bar{x}$) of parasite abundance was calculated for pooled data from each year separately. In 2008 the observed frequency distribution of Anguillicoloides abundance (Figure 5.1) was significantly different from the negative binomial distribution ($\chi^2 = 13.19$, d.f. = 3, $p < 0.05$) but the variance to mean ratio was 1.58 indicating an aggregated distribution. The observed frequency distribution of Anguillicoloides abundance in 2009 (Figure 5.2) was not significantly different from the
negative binomial distribution ($\chi^2 = 6.15$, d.f. = 4, $p > 0.05$) and the variance to mean ratio was 1.21. For the *Anguillicoloides* abundance distribution in 2010 the use of Pearson’s $\chi^2$ test to compare observed distributions with the negative binomial distribution was not appropriate as more than 20% of expected frequencies were less than 5. However, the variance to mean ratio was 1.38 indicating an aggregated distribution (Figure 5.3).

The relationship between infection intensity and eel length for each year is illustrated with scatterplots (Figure 5.4 to Figure 5.6). Spearman’s rank order correlations showed a significant positive correlation between the number of *Anguillicoloides* present and eel length in the samples examined during 2008 ($r_s = 0.65$, $p < 0.001$) and 2010 ($r_s = 0.54$, $p < 0.001$) and no correlation in 2009 ($r_s = 0.10$, $p > 0.05$).

There was no significant correlation ($r_s = 0.09$, $p > 0.05$) between the number of *Anguillicoloides* present in the eels examined and eel condition (data from each year pooled) but there was there a significant difference in condition between infected and non-infected eels (M-W U test, $p < 0.001$). The mean condition values were higher in the infected eels ($K = 0.83$) than in the uninfected eels ($K = 0.63$).
### Table 5.1 Summary statistics for eel length, weight and condition from samples collected at Ardnacrusha during 2008, 2009 and 2010

<table>
<thead>
<tr>
<th>Date</th>
<th>18/7/08</th>
<th>23/7/08</th>
<th>11/8/08</th>
<th>16/6/09</th>
<th>29/7/09</th>
<th>18/6/10</th>
<th>4/8/10</th>
<th>Total</th>
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<tbody>
<tr>
<td>No. of eels</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>29</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>209</td>
</tr>
<tr>
<td>Length (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Min.</td>
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<td>65</td>
<td>62</td>
<td>68</td>
<td>109</td>
<td>63</td>
<td>67</td>
<td>62</td>
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<tr>
<td>Max.</td>
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<td>167</td>
<td>174</td>
<td>180</td>
<td>192</td>
<td>139</td>
<td>164</td>
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<td>123</td>
<td>149</td>
<td>81</td>
<td>82</td>
<td>104</td>
</tr>
<tr>
<td>SD</td>
<td>38</td>
<td>35</td>
<td>26</td>
<td>28</td>
<td>19</td>
<td>20</td>
<td>18</td>
<td>36</td>
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<tr>
<td>Weight (g)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Min.</td>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>1.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
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<tr>
<td>Max.</td>
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<td>4.5</td>
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<td>0.5</td>
<td>1.9</td>
<td>2.6</td>
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<td>0.5</td>
<td>1.3</td>
</tr>
<tr>
<td>SD</td>
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<td>1.1</td>
<td>0.9</td>
<td>1.5</td>
<td>1.0</td>
<td>0.7</td>
<td>0.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Condition (K)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min.</td>
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<td>0.24</td>
<td>0.24</td>
<td>0.31</td>
<td>0.49</td>
<td>0.24</td>
<td>0.33</td>
<td>0.24</td>
</tr>
<tr>
<td>Max.</td>
<td>1.34</td>
<td>1.13</td>
<td>1.00</td>
<td>1.14</td>
<td>1.00</td>
<td>1.23</td>
<td>1.13</td>
<td>1.34</td>
</tr>
<tr>
<td>Mean</td>
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<td>0.65</td>
<td>0.56</td>
<td>0.87</td>
<td>0.75</td>
<td>0.58</td>
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</tr>
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<td>SD</td>
<td>0.28</td>
<td>0.23</td>
<td>0.25</td>
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<td>0.13</td>
<td>0.31</td>
<td>0.18</td>
<td>0.25</td>
</tr>
</tbody>
</table>


Table 5.2 *Anguillicoloides* prevalence, mean intensity and maximum burden for total sample of eels from Ardnacrusha in 2008 and 2009 and 2010

<table>
<thead>
<tr>
<th>Date</th>
<th>No. of eels</th>
<th>Infected eels</th>
<th>Prevalence (%)</th>
<th>Mean intensity</th>
<th>Max. burden</th>
</tr>
</thead>
<tbody>
<tr>
<td>18/7/08</td>
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<td>18</td>
<td>60</td>
<td>2.10</td>
<td>4</td>
</tr>
<tr>
<td>23/7/08</td>
<td>30</td>
<td>12</td>
<td>40</td>
<td>2.08</td>
<td>3</td>
</tr>
<tr>
<td>11/8/08</td>
<td>30</td>
<td>6</td>
<td>20</td>
<td>1.00</td>
<td>1</td>
</tr>
<tr>
<td><strong>2008 Mean</strong></td>
<td></td>
<td></td>
<td><strong>40</strong></td>
<td><strong>1.91</strong></td>
<td></td>
</tr>
<tr>
<td>16/6/09</td>
<td>29</td>
<td>18</td>
<td>62</td>
<td>1.88</td>
<td>4</td>
</tr>
<tr>
<td>29/7/09</td>
<td>30</td>
<td>21</td>
<td>70</td>
<td>2.00</td>
<td>6</td>
</tr>
<tr>
<td><strong>2009 Mean</strong></td>
<td></td>
<td></td>
<td><strong>66</strong></td>
<td><strong>1.94</strong></td>
<td></td>
</tr>
<tr>
<td>18/6/10</td>
<td>30</td>
<td>7</td>
<td>23</td>
<td>1.28</td>
<td>3</td>
</tr>
<tr>
<td>4/8/10</td>
<td>30</td>
<td>7</td>
<td>23</td>
<td>1.42</td>
<td>3</td>
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<td><strong>2010 Mean</strong></td>
<td></td>
<td></td>
<td><strong>23</strong></td>
<td><strong>1.35</strong></td>
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</tbody>
</table>
Figure 5.1 Relative frequency distribution of *Anguillicoloides* in eels from Ardnacrusha in 2008 (N = 90)

![Relative frequency distribution of *Anguillicoloides* in eels from Ardnacrusha in 2008](image)

*Figure 5.1* Relative frequency distribution of *Anguillicoloides* in eels from Ardnacrusha in 2008 (N = 90)

Figure 5.2 Observed *Anguillicoloides* relative frequency distribution (bars) in eels from Ardnacrusha in 2009 and the fit (points) of the negative binomial distribution (N = 59)

![Observed *Anguillicoloides* relative frequency distribution in eels from Ardnacrusha in 2009](image)

*Figure 5.2* Observed *Anguillicoloides* relative frequency distribution (bars) in eels from Ardnacrusha in 2009 and the fit (points) of the negative binomial distribution (N = 59)
Figure 5.3 Relative frequency distribution of *Anguillicoloides* in eels from Ardnacrusha in 2010 (N = 60)
The relationship between eel length and intensity of infection with *Anguillicoloides* at Ardnacrusha in 2008, (N = 90). Correlation is significant (r = 0.65, p < 0.05)

**Figure 5.4** Variation of *Anguillicoloides* infection intensity with eel length at Ardnacrusha in 2009, (N = 59)
Figure 5.6 The relationship between eel length and intensity of infection with *Anguillicoloides* at Ardnacrusha in 2010, (N = 60). Correlation is significant ($r_s = 0.54$, $p < 0.001$)
5.3.2 Parteen

Descriptive statistics for length, weight and condition of eels collected in 2008, 2009 and 2010 are shown in Table 5.3 to Table 5.5. A wide size range of eels (72–435 mm) were examined over the three year period 2008–2010. The mean length of the eels examined was 164 mm.

Details of infection levels of Anguillicoloides recorded in eels sampled in the years 2008–2010 are expressed as prevalence, mean intensity and maximum parasite burden in Table 5.6 to Table 5.8. Prevalence of Anguillicoloides was marginally higher in 2010 (66%) than in 2009 (59%) and 2008 (62%) but there was no significant difference in prevalences between years ($\chi^2 = 5.25$, d.f. = 2, $p > 0.05$). Mean intensity of infection in the samples examined ranged from 1.10 to 2.70 and the maximum parasite burden ranged from 2 to 7. No significant difference in intensity was recorded between years (Kruskal-Wallis ANOVA, $p > 0.05$). No temporal trend in prevalence rates or intensity was apparent when the intra-annual variation was examined. No significant difference in intensity occurred between samples examined within the years 2008 (M-W U, $p > 0.05$) or 2009 (Kruskal-Wallis ANOVA, $p > 0.05$). A significant difference in intensity between samples examined in 2010 was recorded (Kruskal-Wallis ANOVA, $p < 0.05$) but there was no apparent temporal trend in the change in the intensity recorded between the samples.

The data recorded from each sampling date within each year was pooled and the variance to mean ratio ($s^2/\bar{x}$) of parasite abundance was calculated. In each year the variance to mean ratios were $> 1$, indicating overdispersion (aggregation) in the distribution of Anguillicoloides among eel hosts. The observed frequency distributions of Anguillicoloides abundance (Figure 5.7 to Figure 5.9) were not significantly different to a negative binomial distribution in each of the years 2008 ($\chi^2 = 1.61$, d.f. = 4, $p > 0.05$), 2009 ($\chi^2 = 4.30$, d.f. = 4, $p > 0.05$) and 2010 ($\chi^2 = 3.15$, d.f. = 5, $p > 0.05$). In 2010 all of the expected frequencies for more than 5 Anguillicoloides per eel were less
than 1 and it was necessary to form a category of 5 and above or “5+” (Figure 5.9) in order for the result of the $\chi^2$ test to be valid (Dytham, 2003).

The relationship between infection intensity and eel length for the years 2008–2010 is illustrated with scatterplots (Figure 5.10 to Figure 5.12). Spearman rank order correlations showed no correlation between eel length and number of Anguillicoloides present in either 2008 ($r_s = 0.14$, $p > 0.05$) or 2009 ($r_s = 0.06$, $p > 0.05$). In 2010 there was a positive correlation between eel length and number of Anguillicoloides present that was significant ($r_s = 0.27$, $p < 0.01$).

There was no significant correlation ($r_s = 0.04$, $p > 0.05$) between number of Anguillicoloides present in the eels examined and eel condition (data from each year pooled) nor was there a significant difference in condition between infected and non-infected eels (M-W $U$, $p > 0.05$).

Mean prevalence was significantly higher in eels sampled from Parteen than in eels from Ardnacrusha in 2008 ($\chi^2 = 9.68$, d.f. = 1, $p < 0.05$) and 2010 ($\chi^2 = 37.43$, d.f. = 1, $p < 0.05$). In 2009 prevalence in eels from Ardnacrusha and Parteen were not significantly different ($\chi^2 = 1.05$, d.f. = 1, $p > 0.05$) but the prevalence recorded from the Ardnacrusha sample (66%) was somewhat higher than that recorded from the Parteen sample (59%). The mean intensity of Anguillicoloides infection was similar in eels sampled from Ardnacrusha and Parteen in 2008 and 2009, ranging from 1.90 to 2.0 but in 2010 the mean intensity recorded in eels from Ardnacrusha was lower (1.35) than that recorded from the Parteen sample (1.9). The lowest mean prevalence (23%) was also recorded in the Ardnacrusha sample in that year.
Table 5.3 Summary statistics for eel length, weight and condition from samples collected at Parteen during 2008

<table>
<thead>
<tr>
<th>Date</th>
<th>6/6/08</th>
<th>29/7/08</th>
<th>Total</th>
</tr>
</thead>
<tbody>
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<td>50</td>
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</tr>
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<td>80</td>
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<tr>
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<td>256</td>
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<td>148</td>
</tr>
<tr>
<td>SD</td>
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<td>42</td>
</tr>
<tr>
<td>Weight (g)</td>
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</tr>
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<td>0.4</td>
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<td>Max.</td>
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<td>28.0</td>
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<td>0.56</td>
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<td>Mean</td>
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</table>
Table 5.4 Summary statistics for eel length, weight and condition from samples collected at Parteen during 2009

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<th>Total</th>
</tr>
</thead>
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<td>59</td>
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<td><strong>Length (mm)</strong></td>
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<td>141</td>
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<tr>
<td>SD</td>
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<td>29</td>
<td>49</td>
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<td>87.4</td>
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<td></td>
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<td>0.96</td>
<td>0.86</td>
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Table 5.5 Summary statistics for eel length, weight and condition from samples collected at Parteen during 2010

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<td>15</td>
<td>15</td>
<td>15</td>
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<td>0.3</td>
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<td>44.1</td>
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<td>11.9</td>
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<td>4.4</td>
<td>5.1</td>
<td>6.3</td>
<td>8.9</td>
<td>11.1</td>
<td>7.9</td>
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<tr>
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<td></td>
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</tr>
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<td>0.73</td>
<td>0.72</td>
<td>0.96</td>
<td>0.42</td>
<td>0.27</td>
<td>0.73</td>
<td>0.71</td>
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<td>0.88</td>
<td>0.27</td>
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<td>1.47</td>
<td>1.69</td>
<td>1.54</td>
<td>1.39</td>
<td>1.54</td>
<td>1.57</td>
<td>1.39</td>
<td>1.40</td>
<td>1.48</td>
<td>1.53</td>
<td>1.36</td>
<td>1.69</td>
</tr>
<tr>
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<td>0.99</td>
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<td>0.28</td>
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<td>0.14</td>
<td>0.23</td>
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Table 5.6 *Anguillicoloides* prevalence, mean intensity and maximum burden for total sample of eels from Parteen in 2008

<table>
<thead>
<tr>
<th>Date</th>
<th>No. of eels</th>
<th>Infected eels</th>
<th>Prevalence (%)</th>
<th>Mean intensity</th>
<th>Max. burden</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/6/08</td>
<td>20</td>
<td>14</td>
<td>70</td>
<td>1.93</td>
<td>4</td>
</tr>
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<td>1.88</td>
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<tr>
<td>2008 Mean</td>
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<td>62</td>
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</table>

Table 5.7 *Anguillicoloides* prevalence, mean intensity and maximum burden for total sample of eels from Parteen in 2009

<table>
<thead>
<tr>
<th>Date</th>
<th>No. of eels</th>
<th>Infected eels</th>
<th>Prevalence (%)</th>
<th>Mean intensity</th>
<th>Max. burden</th>
</tr>
</thead>
<tbody>
<tr>
<td>26/6/09</td>
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<td>16</td>
<td>53</td>
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<td>4</td>
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<tr>
<td>27/7/09</td>
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<td>65</td>
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</table>
Table 5.8 *Anguillicoloides* prevalence, mean intensity and maximum burden for total sample of eels from Parteen in 2010

<table>
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<tr>
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<th>No. of eels</th>
<th>Infected eels</th>
<th>Prevalence (%)</th>
<th>Mean intensity</th>
<th>Max. burden</th>
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<td>67</td>
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<td>5</td>
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<td>60</td>
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<td>2</td>
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<td>7</td>
<td>47</td>
<td>2.00</td>
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Figure 5.7 Observed *Anguillicoloides* relative frequency distribution (bars) in eels from Parteen in 2008 and the fit (points) of the negative binomial distribution (N = 50)

Figure 5.8 Observed *Anguillicoloides* relative frequency distribution (bars) in eels from Parteen in 2009 and the fit (points) of the negative binomial distribution (N = 59)
Figure 5.9 Observed *Anguillicoloides* relative frequency distribution (bars) in eels from Parteen in 2010 and the fit (points) of the negative binomial distribution (N = 180)
Figure 5.10 Variation of *Anguillicoloides* infection intensity with eel length at Parteen, 2008 (N = 50)

Figure 5.11 Variation of *Anguillicoloides* infection intensity with eel length at Parteen, 2009 (N = 59)
Figure 5.12 The relationship between eel length and intensity of infection with *Anguillicoloides* at Parteen 2010 (N = 180). Correlation is significant ($r_s = 0.27$, $p < 0.05$)
5.3.3 River Erne

On July 12th 2010 a sample of 44 eels (Table 5.9) were collected from the Cathaleen’s Fall juvenile eel trap and examined for the presence of *Anguillicoloides* using the same protocol. Infection levels (Table 5.10) were low (prevalence = 14%, mean intensity = 1) in comparison to those recorded in the Shannon system at Parteen and Ardnacrusha.

**Table 5.9** Summary statistics for eel length, weight and condition from samples collected at Cathaleen’s Fall in 2010

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<th>Condition (K)</th>
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<td>Min.</td>
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<td></td>
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<td>SD 45</td>
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**Table 5.10** *Anguillicoloides* prevalence, mean intensity and maximum burden for eels sampled from the Cathaleen’s Fall juvenile eel trap in 2010

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<th>Prevalence (%)</th>
<th>Mean intensity</th>
<th>Max. burden</th>
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<td>14</td>
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</table>
5.3.4 River Lee
Eels were collected from the Inniscarra juvenile eel trap in October 2008 and August 2009 and from a sample collected below the Inniscarra juvenile eel trap in the River Lee by electrofishing in September 2010. Descriptive statistics for length, weight and condition of the eels examined are shown in Table 5.11. A length frequency distribution of all of the eels (N = 118) collected by electrofishing in September 2010 and the sub-sample (N = 30) examined for the presence of *Anguillicoloides* is shown in Figure 5.13. Over the three years 73 eels in total were examined and no *Anguillicoloides* were present.

**Table 5.11** Summary statistics for eel length, weight and condition from samples collected on the River Lee during 2008, 2009 and 2010

<table>
<thead>
<tr>
<th>Date</th>
<th>14/10/2008</th>
<th>19/8/2009</th>
<th>1/9/2010</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No. of eels</strong></td>
<td>17</td>
<td>26</td>
<td>30</td>
</tr>
<tr>
<td><strong>Length (mm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min.</td>
<td>90</td>
<td>98</td>
<td>107</td>
</tr>
<tr>
<td>Max.</td>
<td>110</td>
<td>157</td>
<td>227</td>
</tr>
<tr>
<td>Mean</td>
<td>92</td>
<td>129</td>
<td>139</td>
</tr>
<tr>
<td>SD</td>
<td>10</td>
<td>15</td>
<td>27</td>
</tr>
<tr>
<td><strong>Weight (g)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min.</td>
<td>0.3</td>
<td>0.7</td>
<td>1.5</td>
</tr>
<tr>
<td>Max.</td>
<td>1.1</td>
<td>4.1</td>
<td>15.2</td>
</tr>
<tr>
<td>Mean</td>
<td>0.6</td>
<td>2.3</td>
<td>4.1</td>
</tr>
<tr>
<td>SD</td>
<td>0.3</td>
<td>0.9</td>
<td>2.9</td>
</tr>
<tr>
<td><strong>Condition (K)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min.</td>
<td>0.56</td>
<td>0.79</td>
<td>1.12</td>
</tr>
<tr>
<td>Max.</td>
<td>0.97</td>
<td>1.26</td>
<td>1.60</td>
</tr>
<tr>
<td>Mean</td>
<td>0.77</td>
<td>1.03</td>
<td>1.37</td>
</tr>
<tr>
<td>SD</td>
<td>0.11</td>
<td>0.12</td>
<td>0.14</td>
</tr>
</tbody>
</table>
Figure 5.13 Length frequency distribution of eels sampled by electrofishing in the River Lee, below the Inniscarra hydropower station, 1/9/2010
5.4 Discussion

Information on the disease status of eel populations is required in order to identify and protect areas producing high quality spawners (Belpaire et al., 2011). This study presents information on the *Anguillicoloides* infection parameters recorded in migrating juvenile eels from the Shannon and Erne River systems. The previously reported *Anguillicoloides* free status of the eel population of the River Lee is supported by the findings of this study also.

Severe pathological symptoms such as haemorrhaging in, and thickening of the swimbladder wall can manifest in eels of all sizes and infection by *Anguillicoloides* leaves host fish more susceptible to other environmental stress (Székely et al., 2009). Documented cases of parasite induced host mortality in wild eel populations are quite rare and are usually associated with stress inducing factors such as high eel densities, high water temperatures and low dissolved oxygen levels (Kirk, 2003). Nimeth et al. (2000) concluded that based on the severe damage to the swimbladder of glass eels caused by *Anguillicoloides* infection observed in their experiments, the viability of infected eels would be reduced. Palstra et al. (2007) have demonstrated that infection and damage of the swimbladder of silver eels by *Anguillicoloides* impairs swimming performance and increases the overall energy consumption of eels and is therefore a serious threat to the reproductive success of European eels. In this present study damage to the swimbladder wall of infected eels was noticed occasionally, however, infected eels were typically in good condition.

*Anguillicoloides* was initially recorded in the Shannon River system in migrating silver eels captured at Killaloe in 1998. In the following years, eels captured in the yellow eel fishery in the Shannon were examined for the presence or absence of *Anguillicoloides* revealing relatively low infection rates (prevalence of 20% was recorded in Lough Derg in 2002) and its spread up the catchment (Anon., 2002). The rapid spread of *Anguillicoloides* in a river system once it has been introduced and also the initial rapid
increase in infection intensity has been observed in *Anguilla anguilla* (Kennedy and Fitch, 1990; Wickström *et al.*, 1998) and *Anguilla rostrata* (Barse *et al.*, 2001) populations.

The mean prevalence of *Anguillicoloides* was as high as 66% in eels from both Parteen (2010) and Ardnacrusha (2009) during this study. Mean prevalence ranged from 59–66% in Parteen (Table 5.6 to Table 5.8) and a much greater variation in mean prevalence was recorded at Ardnacrusha (23–66%) (Table 5.2). Similar prevalence rates have been reported for eels of the same size range in studies by Thomas and Ollevier (1992) and Lefebvre *et al.* (2002). In a review of long term studies of *Anguillicoloides* infection in wild European eel stock a general pattern emerged whereby there was an initial rapid increase in prevalence within a few years following introduction and subsequently, although values fluctuate, prevalence appears to stabilise around a specific level of 50–90% (Knopf, 2006). The mean prevalence of *Anguillicoloides* in eels sampled from Parteen appears quite stable but the fluctuations in mean prevalence in eels from Ardnacrusha may be caused by a number of possible factors such as variations in eel or intermediate host density and lower parasite transmission rate in waters with higher salinity (Norton *et al.*, 2005).

A significant positive correlation between eel length and *Anguillicoloides* abundance was found in one year at Parteen (Figure 5.1) and in two years at Ardnacrusha (Figure 5.4 and Figure 5.6). This finding is in agreement with that of a number of other authors (Thomas and Ollevier, 1992; Audenaert *et al.*, 2003; Schabuss *et al.*, 2005) who found that larger eels harboured more parasites. The explanation for increased parasite abundance in larger eels has been attributed to a longer exposure time of older (larger) eels to the parasite and a higher consumption of infected prey with increasing host size (Schabuss *et al.*, 2005). This trend is not always seen and significant negative correlations between eel size and *Anguillicoloides* abundance have been reported by Morrissey and McCarthy (2007) and Fazio *et al.* (2008). In these studies it has been
speculated that the negative correlation may have resulted from unusual features of the habitats and the trophic ecology of the eels. Morrissey and McCarthy (2007) suggest that the larger eels from the mixohaline waters in their study were more likely to have consumed crabs *Carcinus maenas* than infected paratenic hosts. Fazio (2008) speculates that transmission rates of *Anguillicoloides* by paratenic hosts may be lower than by intermediate hosts in Mediterranean lagoons and that decreased parasite abundance in older eels may be explained by higher mortality rate among the oldest infected eels and therefore their resulting absence in the samples.

There was no significant correlation between the number of *Anguillicoloides* present and Fulton’s condition factor (*K*) in eels sampled at either Ardnacrusha or Parteen. This result is in agreement with a number of other studies (Thomas and Ollevier, 1992; Würtz *et al*., 1998; Morrissey and McCarthy, 2007) which have typically examined eels of a greater size range and where the range of infection intensities observed were also wider.

A significant difference in eel condition was recorded between eels infected with *Anguillicoloides* and those free of infection in the samples taken from Ardnacrusha. This result was contrary to expectations, as the infected eels had significantly higher condition values (M-W *U*, *p* < 0.05). Moller *et al*. (1991) found a similar result in that no significant impact of *Anguillicoloides* infection on host condition occurred but heavily infected eels showed a slightly but not statistically significant higher condition factor. Likewise Costa-Dias *et al*. (2010) found a counterintuitive pattern in that higher condition values were recorded in heavily infected eels but the authors suggested that this pattern may be associated with covariate factors not related to infection as eels were sampled from different habitats along the river gradient. Moller *et al*. (1991) also pointed out that condition factor in wild eels is more variable than in other fish species and differences between groups are difficult to detect.
Kirk (2003) has suggested that the reason that the loss in body weight of wild infected eels has not been demonstrated may be because infected eels are better nourished through feeding on piscine paratenic hosts. Molnar et al. (1994) found that larger eels had higher parasite burdens and suggested this may be partly explained by the fact that smaller fish consume less infected intermediate or paratenic hosts.

The result found in this study may reflect the limitations of weight-length condition indices that are used to estimate physiological fitness in eels. In fish body form changes with length and Fulton’s condition factor ($K$) is length dependent with $K$ increasing with increasing length, limiting its application to fish of similar length (Pope and Kruse, 2007). Weight is especially variable in eels and good feeding conditions can cause an eel’s weight to be twice that of another of equal length (Tesch, 2003). Physiological measures of condition provide a more precise measure of fish fitness in terms of stored energy than condition indices which are intended to estimate physiological condition indirectly based on individual whole-body mass. Physiological measures include the use of either an index of tissue weights or direct measures of lipid (Svedäng and Wickström, 1997) or protein content (Boetius and Boetius, 1985) or RNA/DNA ratios (Kawakami et al., 1999) which are indicators of protein synthesis rate (Pope and Kruse, 2007). Recently Fazio et al. (2009) examined the effect of Anguillicoloides on the expression of genes involved in processes such as growth, osmoregulation and stress tolerance in eels during their continental life stage and their results showed an absence of an effect on genes involved in eel growth.

The calculated values of the variance to mean ratio ($s^2/\bar{x}$) of parasite abundance in eels collected in Ardnacrusha and Parteen was $> 1$ in all years indicating a high degree of aggregation. In samples collected from Parteen the parasite distribution was not significantly different from the negative binomial distribution in each of the years 2008–2010 and the exponent ($k$) of the negative binomial distribution varied from 0.92 (highly overdispersed distribution, where most of the parasites are living in just a few heavily
infected eels) to 5.9 (Figure 5.7 to Figure 5.9). These results are in agreement with the findings in a number of other studies (Thomas and Ollevier, 1992; Ashworth and Kennedy, 1999; Norton et al., 2005) and are characteristic for the vast majority of macroparasite distributions (Wilson et al., 2001). An indirect measure of parasite-induced mortality can be derived if the infection frequency data fits the negative binomial distribution (Bernies et al., 2011). According to the theoretical work of Crofton (1971), cited by (Bernies et al., 2011), values of $k > 1$ indicate parasite-induced mortality and such values will only occur if disproportionate morbidity removes hosts with more severe infection from the population. There are, however, other factors affecting parasite density besides host mortality that might reduce the sensitivity of the $k$ value as a measure of parasite-induced mortality (Bernies et al., 2011), e.g. the host’s feeding preference and the trophic state of the water body.

*Anguillocoeloides* is thought to have invaded the Erne catchment sometime around 1996 or 1998 (Copley and McCarthy, 2005). The first record of *Anguillocoeloides* in the Erne river system was documented by Evans and Matthews (1999) in yellow eels captured in a fyke net survey undertaken in the catchment in 1998 and subsequent screening of eels for the presence or absence of *Anguillocoeloides* in 1999 showed that the highest prevalence (20.2%) was found in eels from Lower and Upper Lough Erne (Evans et al., 2001). In 2008 prevalence of *Anguillocoeloides* in yellow eels sampled from the commercial eel fishery was 56.4% (ICES, 2009). In the present study the prevalence recorded from a sample of juvenile eels was low in comparison at 14%.

It may be that the difference between the prevalence recorded in this study and that recorded in the 2008 survey (ICES, 2009) is due to the different size class of eels examined. Thomas and Ollevier (1992) did not find any difference in prevalence among various size classes in their study of eels in Belgium. However, all of their eels were sampled from a relatively small (720 m²) canal area where likelihood of encountering the parasite may have been more equitable. In the case of the Erne River system the
elvers and juvenile eels in this survey were collected from a trap located at the tidal limit of the Erne and the yellow eels examined in the other surveys (Evans et al., 2001; ICES, 2009) were collected from lacustrine freshwater habitats in Lower and Upper Lough Erne where abundance of infected intermediate hosts may vary. The salinity of the estuarine waters in the Erne may also help explain the lower prevalence recorded in juvenile eels. In the Elbe estuary in Germany Taraschewski et al. (1987) found a decrease in prevalence towards the open sea and speculated that transmission of infection may be restricted to freshwater and low salinity environments.

The mean intensity of infection recorded in the sample taken from the Erne in this study (Table 5.10) was also low in comparison to the mean intensity recorded by Evans et al. (2001) for yellow eels from the Erne. It was also low compared to the mean intensity recorded for a similar size range of eels collected at Ardnacrusha during this survey (Table 5.2). Evans et al. (2001) found that prevalence and mean intensity varied widely between sites and reported that the rapid increase in prevalence and mean intensity of Anguillicoloides following its introduction to new waters was not observed in the Erne. Factors such as the relatively low water temperatures and low eel densities in the Erne system may explain these differences to some extent (Evans et al., 2001).

Anguillicoloides was not present in the juvenile eels examined from the River Lee system. This result is in agreement with investigations carried out by McCarthy et al. (2008b) where they examined eels captured by electrofishing, fyke net and longline fishing methods in lacustrine and riverine areas. This probably reflects the lack of commercial eel fishing in the area as transport of live eels has been linked to its spread (Kennedy and Fitch, 1990). Protection of the Lee eel stocks from Anguillicoloides and other pathogens that can affect the quality of spawners leaving the river as silver eels is still very important (McCarthy et al., 2008b). Commercial eel fishing and angling for eels has been prohibited in Ireland since 2009 (Anon., 2009a), however, threats to the Anguillicoloides free status of eels in the River Lee system still exist. Illegal eel fishing...
in the area has been documented in the past (Lucey, 2008) and the spread of Anguillicoloides may be facilitated by movement of fishing gear and boats from areas where the parasite is already established or by the transfer of water (used to transport live eels) from infected areas. Introduction of Anguillicoloides is also possible through illegal stocking of infected paratenic host fish species by anglers or the accidental release of such live fish used for the illegal practice of live baiting.

The occurrence of Anguillicoloides in juvenile eels migrating upriver in the Shannon and Erne systems highlights another dispersal route of the parasite. The expansion of the parasite’s range to the uppermost areas of those river systems and to tributaries of the Shannon and Erne estuaries is possible through the natural migration of infected juvenile eels.

The presence of Anguillicoloides in juvenile eels that could be used for stocking has implications for the choice of management strategy selected. The report of the 2007 joint ICES/EIFAC working group on eels (ICES, 2007) recommended that eels used for stocking should be free of Anguillicoloides and should have “as near perfect health status as possible”. Up until 2008 small amounts of glass eels collected in the Shannon estuary and neighbouring catchments were stocked to areas of the Shannon catchment above the Ardnacrusha hydroelectric power station and the Parteen regulating weir. This practice has since been discontinued because of the widespread presence of Anguillicoloides in the Shannon catchment. It has been proposed that in the event of recovering recruitment levels “surplus” recruits will be stocked to good quality catchments free of Anguillicoloides (Anon., 2008a). Therefore it is necessary that the occurrence and distribution of Anguillicoloides is known in the juvenile eels used as stocking material and in eel populations of catchments where juvenile eels will be distributed.
Chapter 6  Size selectivity and efficiency estimates of juvenile eel trapping facilities at the Parteen regulating weir

6.1  Size selectivity of different trap substrates

6.1.1  Introduction

The ability of juvenile eels to use conventional fish passes at obstacles such as dams and weirs is limited due to high water velocity and strong turbulence. However, their capacity for climbing has long been recognised and juvenile eels with their long and relatively light bodies can even climb almost vertical walls that are not too smooth. Juvenile eel trap designs facilitate and encourage the climbing behaviour of eels by providing reduced water speeds and a suitable climbing substrate (Tesch, 2003). Different substrate types are suitable for different size classes of eels and a variety of substrate types may be required to accommodate the entire size range of potential upstream migrating eels. At Parteen the climbing substrate of the existing juvenile eel trap (described in Chapter 3) consists of tufts of nylon bristle at 10 mm centers in staggered rows. In this study additional traps were deployed below the Parteen regulating weir that had different substrate types to that of the existing eel trap. The size selectivity and performance of each trap was examined and compared to the existing trap to determine if an increased size range of upriver migrating eels could be collected at the Parteen regulating weir through the use of traps with alternative substrate types.

6.1.2  Methods and Materials

Trapping undertaken in 2008

Juvenile eel trapping was undertaken at a new location at the Parteen regulating weir during the 2008 juvenile eel migration in addition to the main juvenile eel trap. The traps were installed downstream of the existing Parteen juvenile eel trap at the base of a pipe discharging water from the Parteen hatchery on June 5th. Four traps modified from the O’ Leary (1971) design were placed in series, parallel to the riverbank (Figure 6.1; Plate 6.2a). The traps were 1.2 m long and 0.4 m wide and each trap was provided with
a c. 30 litres per minute$^{-1}$ water supply to encourage eels to climb a substrate covered ramp. Once eels ascended the ramp to the groove at the top, they entered into the high velocity stream of water in the groove and were washed into a pipe and down into a plastic mesh (1 mm spacing) holding bag.

Three different substrate types were used, with two of the traps using the same substrate type, i.e. a brush substrate. The brush substrate was composed of plastic bristles that were densely laid out (1.75 cm between tufts) on one side of a ramp and sparsely laid out (2.5 cm between tufts) on the other side (Plate 6.1). The brush substrate was used on two traps so that on one trap the densely laid side was closest to the river bank (Brush d/b) and in the other the densely laid side was closest to the river channel (Brush d/r). The other two substrate types used were commercial versions, one using compact urethane foam channels with 25 mm diameter studs and the other a plastic ramp with dome-like protrusions 30 mm in height with 14 mm gaps (Plate 6.1). Traps were inspected in the morning (0900 - 1200 hours) and all of the eels captured were measured for length and the weight of the total catch for each trap was recorded.

**Trapping undertaken in 2009 and 2010**

In 2009 three new juvenile eel traps were installed adjacent to the outflow from the Parteen pool and traverse fish pass and the existing Parteen juvenile eel trap on June 8$^\text{th}$ (Plate 6.2b and Plate 6.3). Each trap consisted of fiberglass ramps that measured 0.4 m in width and 5 m in length. Two different substrate types were used for the ramps of the traps which lead to individual holding tanks thereby allowing a comparison of the percentage length frequency distributions of eels captured in each trap. Two of the traps used plastic bristles as the climbing substrate while the third trap used sections of PVC tubes protruding from a wooden ramp. The tufts of plastic bristles were set in a wooden board in staggered rows. One ramp (Trap 1) had a more dense arrangement of bristles with the space between the tufts of bristles being 1.75 cm and on the second ramp (Trap 2) the space was increased to 2.5 cm. The third ramp consisted of a series of staggered PVC tubes (36 mm diameter) that were laid in staggered rows 4.5 cm apart intended for
the eels to push against as they ascend (Plate 6.3). Each trap had a separate holding tank (225 l volume) and water supply (c. 30 litres per minute\(^{-1}\)). Water for each ramp was provided from the holding tank attached to that ramp. At the top of each ramp where it entered the holding tank a perforated water pipe sprayed water to the ramp and also into the holding tank so that once the eels reached the top of the ramp they were flushed into the holding tank (Plate 6.4). Three additional pipes were used to discharge water over the surface at the base of each ramp where it entered the river with the aim of increasing the attraction flow.

**Figure 6.1** Elver trap design by O’Leary (1971)

**Plate 6.1** Substrate types used in trapping studies undertaken in 2008. (a) brush substrate, (b) compact urethane channels, (c) plastic ramp with dome-like protrusions
Plate 6.2 Experimental traps used at Parteen in 2008 (a) and those used in 2009 and 2010 (b)

Plate 6.3 Plastic brush and PVC tube climbing substrates used in 2009 and 2010

Plate 6.4 Holding tanks and water supply for the juvenile eel traps used in 2009 and 2010
6.1.3 Results

Trapping undertaken in 2008

The traps were in operation for 42 nights during the months of June, July, August and September. The total catch weights made in each trap are given in Table 6.1. The highest catches were made in the trap using the compact urethane substrate (1275 g) and the brush substrates (958 g and 572 g).

The results from length measurements recorded from eels captured on each substrate type are shown in Table 6.2. The mean length of all of the eels sampled from the experimental traps combined was 125 mm ± 32, with a range of 77 mm to 308 mm. This was lower than the mean length of the eels sampled from the existing Parteen juvenile eel trap which was 155 ± 38 mm (Table 6.2) and their size distributions were significantly different (Mann-Whitney U-test, p < 0.001). A percentage length frequency distribution graph for the eels captured using the experimental traps and the existing trap is shown in Figure 6.2.

There was a no significant difference in the length frequency distributions of eels captured in the two experimental traps that used the brush substrate (Mann-Whitney U-test, p > 0.05). The size distributions of eels caught using these substrates were significantly different to that of the existing trap (Mann-Whitney U-test, p < 0.001). The minimum and mean length of the eels captured using brush substrate was also smaller than for those captured in the existing trap which suggests they are better suited to capture of smaller eels.

The trap using the plastic dome-like substrate performed poorly in comparison to the other substrate types and the sample size was low. The compact urethane substrate performed better and the eels captured by it were significantly different in length to the existing Parteen trap and to the traps using brush substrate (Mann-Whitney U-test, p <
The compact urethane substrate captured a greater proportion of eels larger than 150 mm in length than that of the brush lined experimental traps. The relative length frequencies eels captured using the existing Parteen trap, the brush substrate traps and the compact urethane lined trap is shown in Figure 6.3.

**Table 6.1** Summary of catch data from each experimental trap by numbers of eels capture, total catch weight and mean weight of eels in 2008

<table>
<thead>
<tr>
<th>Substrate</th>
<th>N</th>
<th>Total catch weight (g)</th>
<th>Mean weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brush d/b</td>
<td>346</td>
<td>958</td>
<td>2.8</td>
</tr>
<tr>
<td>Brush d/r</td>
<td>198</td>
<td>572</td>
<td>2.9</td>
</tr>
<tr>
<td>Plastic dome</td>
<td>73</td>
<td>247</td>
<td>3.4</td>
</tr>
<tr>
<td>Compact urethane</td>
<td>406</td>
<td>1275</td>
<td>3.1</td>
</tr>
</tbody>
</table>

**Table 6.2** Summary of length (mm) data from eels captured in traps with different substrate types in 2008

<table>
<thead>
<tr>
<th>Substrate</th>
<th>N</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brush d/b</td>
<td>262</td>
<td>120</td>
<td>77</td>
<td>230</td>
<td>31</td>
</tr>
<tr>
<td>Brush d/r</td>
<td>174</td>
<td>122</td>
<td>82</td>
<td>223</td>
<td>27</td>
</tr>
<tr>
<td>Plastic dome</td>
<td>54</td>
<td>137</td>
<td>90</td>
<td>246</td>
<td>44</td>
</tr>
<tr>
<td>Compact urethane</td>
<td>371</td>
<td>129</td>
<td>78</td>
<td>308</td>
<td>34</td>
</tr>
<tr>
<td>Experimental Traps (combined)</td>
<td>861</td>
<td>125</td>
<td>77</td>
<td>308</td>
<td>33</td>
</tr>
<tr>
<td>Main Trap</td>
<td>3857</td>
<td>155</td>
<td>80</td>
<td>329</td>
<td>38</td>
</tr>
</tbody>
</table>
Figure 6.2 Percentage length frequency distributions of eels captured using experimental traps and the main Parteen trap in 2008.

Figure 6.3 Percentage length frequency distributions of eels captured using traps with two different substrate types and the main Parteen trap in 2008.
Trapping undertaken in 2009 and 2010

During the 2009 migration season the total weight of juvenile eels captured at Parteen was remarkably low with 139 kg of eels captured in the main Parteen trap in comparison to 1305 kg recorded in 2008. Sampling of eels captured in the new traps was carried out on two dates and a summary of the length data from eels captured is presented in Table 6.3. No eels were captured in the third trap which had the plastic tube climbing substrate.

Table 6.3 Summary of length (mm) data from eels captured in traps with different substrate types in 2009

<table>
<thead>
<tr>
<th>Trap</th>
<th>N</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trap 1</td>
<td>12</td>
<td>108</td>
<td>82</td>
<td>257</td>
<td>48</td>
</tr>
<tr>
<td>Trap 2</td>
<td>13</td>
<td>100</td>
<td>84</td>
<td>167</td>
<td>22</td>
</tr>
<tr>
<td>Combined</td>
<td>25</td>
<td>104</td>
<td>82</td>
<td>257</td>
<td>36</td>
</tr>
</tbody>
</table>

In 2010 the experimental traps installed at Parteen in 2009 were again operated and monitored. The traps were put in operation over a total of 23 nights during the months of June, July, August and September. The total catch weights made in each trap are given in Table 6.4. Catches were particularly low in trap 3. The mean weight per eel captured in trap 1 and trap 2 were similar (1.1 g and 1.0 g).

Eels were sampled for measurement on 5 occasions and each time all of the eels present were measured to provide a representative sample. A summary of length data from eels captured is presented in Table 6.5 and a percentage length frequency distribution is shown in Figure 6.3.

Trap 3 which used a substrate made of PVC pipes performed poorly in 2010 capturing just 11 eels in total and this may be due to the fact that the space between the PVC pipes
is too wide to assist small bootlace eels to ascend the ramp. There was a significant difference in the size of eels captured in trap 1 which had a dense arrangement of bristle and trap 2 which had a more sparse array of bristles (Mann-Whitney U-test, p < 0.001) with smaller eels more abundant in catches made by trap 1 (Table 6.5). The mean and minimum sizes of eels captured in traps 1 and 2 were quite similar however and in both cases were lower than those of the existing Parteen trap. There was a significant difference between the lengths of eels captured in both of the experimental traps (trap 1 and 2) compared with the existing Parteen trap (Mann-Whitney U-test, p < 0.001). As with the experimental traps used in 2008, the experimental traps used in 2010 captured a greater proportion of smaller eels in comparison to the existing trap (Figure 6.4).

**Table 6.4** Summary of catch data from each experimental trap by numbers of eels capture, total catch weight and mean weight of eels in 2010

<table>
<thead>
<tr>
<th>Trap</th>
<th>N</th>
<th>Total catch weight (g)</th>
<th>Mean weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trap 1 Brush</td>
<td>183</td>
<td>200</td>
<td>1.1</td>
</tr>
<tr>
<td>Trap 2 Brush</td>
<td>301</td>
<td>277</td>
<td>1.0</td>
</tr>
<tr>
<td>Trap 3 Tube</td>
<td>11</td>
<td>28</td>
<td>2.5</td>
</tr>
</tbody>
</table>

**Table 6.5** Summary of length (mm) data from eels captured in traps with different substrate types in 2010

<table>
<thead>
<tr>
<th>Trap</th>
<th>N</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trap 1 Brush</td>
<td>83</td>
<td>92</td>
<td>64</td>
<td>122</td>
<td>15</td>
</tr>
<tr>
<td>Trap 2 Brush</td>
<td>204</td>
<td>103</td>
<td>64</td>
<td>180</td>
<td>18</td>
</tr>
<tr>
<td>Trap 3 Tube</td>
<td>11</td>
<td>105</td>
<td>70</td>
<td>200</td>
<td>36</td>
</tr>
<tr>
<td>New traps combined</td>
<td>298</td>
<td>100</td>
<td>64</td>
<td>200</td>
<td>19</td>
</tr>
<tr>
<td>Main Trap</td>
<td>372</td>
<td>151</td>
<td>82</td>
<td>316</td>
<td>47</td>
</tr>
</tbody>
</table>
Figure 6.4 Percentage length frequency distributions of eels captured in traps with different densities of brush substrates and the main Parteen trap in 2010
6.1.4 Discussion

In electrofishing surveys carried out in this study at different sites on the lower River Shannon during 2009 (see section 6.3) much larger eels were sampled than were captured in the juvenile eel traps at Parteen. A proportion of these larger eels are likely to be resident eels that will not migrate further upriver. However, it is also possible that the existing trap at Parteen is not suitable for capturing these larger eels due to the dense arrangement of the brush substrate. In previous studies undertaken at the Parteen trap when a different trap design and brush substrate was used, higher proportions of eels in the size class 200–300 mm $L_T$ were present in samples (Moriarty, 1986).

In 2008 the eel catch weights recorded from the experimental trap were low despite the traps operating over a period of 42 nights (Table 6.1). The traps were located approximately 50 m downstream of the weir at an outflow pipe of the Parteen hatchery where eels have been observed moving up the pipe in the past (T. O’Brien, pers. comm.). Juvenile eels are attracted to flowing water as an indicator for suitable migration routes and tend to gather at the most upstream point beneath obstructions, close to the main flow (Solomon and Beach, 2004). The discharge of water from the outflow pipe was small relative to the discharge from the pool and traverse fish pass and it is likely that it was less attractive to migrating eels seeking out a route upriver. In addition to this, the experimental traps were located further downstream from the weir than the main trap where eels were less likely to congregate, further reducing the effectiveness of the traps.

The eels captured in the experimental traps used in 2008 were significantly smaller than those captured in the main trap (Figure 6.2). The two traps with the brush substrate captured a greater proportion of smaller eels than the trap with the compact urethane substrate or the main trap (Figure 6.3) suggesting the use of the additional traps using a brush substrate with variable spacing could be beneficial for catching smaller juvenile eels. The third trap which used a substrate composed of a plastic ramp with dome-like
protrusions was considerably less effective than the other substrate types used. One reason for this may be that the smooth plastic surface was not suitable for efficient movement up the ramp as the studs did not allow sufficient purchase for eels to employ their natural crawling ability.

The experimental traps used in 2009 and 2010 performed poorly relative to the main trap in terms of total catch weight. The experimental traps were located closer to the weir than in 2008 and were adjacent to the outflow of the pool and traverse fish pass (Plate 6.2b), however, similar problems in providing sufficient attraction flows to the experimental traps were encountered as in 2008. An effort was made to provide additional attraction flow to the experimental traps using pipes that discharged water over the base of each ramp where it entered the river.

Trap 3 (consisted of a series of staggered PVC tubes) performed poorly in comparison to the brush substrates. The spacing between the individual tubes (4.5 cm) was intended to facilitate the capture of larger juvenile eels than were captured in the main Parteen trap. However, very few eels were captured and their mean length was 105 mm. It is likely that the spacing between the tubes was too wide to attract most eels that encountered the trap and as in the case of the plastic substrate with the dome-like protrusions used in 2008 the smooth surface of this substrate did not provide effective purchase for eels as they attempted to crawl up the ramp. The other two traps using brush substrate of varying density (Trap 1; 1.75 cm spacing. Trap 2; 2.5 cm spacing) were more effective in comparison to Trap 3. There was a significant difference between the length frequency distributions of eels captured from trap 1 and trap 2 and the selectivity of the different densities of brush substrate used was evident. Eels captured in trap 1, with its tightly arranged tufts of bristles, were significantly smaller eels than eels captured in trap 2 where there was a greater distance between the tufts. Similar to the result from the experimental trapping in 2008 eels captured in the new traps in 2010 using brush substrates were significantly smaller than those captured in the main trap.
Size selectivity of different substrate types in juvenile eel traps has also been reported elsewhere (Legault, 1992; Solomon and Beach, 2004) where dense brush substrates result in the capture of smaller eels. Providing additional traps at optimal locations, close to the weir and major attraction flows where eels are more likely to congregate, could improve the effectiveness of the trapping program at Parteen. In any additional traps it would be necessary to use a wider range of differing brush densities than are currently in use in the main trap in order to facilitate the complete size range of the migrating population.
6.2 Mark and recapture experiments undertaken at the Parteen juvenile eel trap

6.2.1 Introduction

To assess the catch efficiency of the juvenile eel trap located adjacent to the entrance of the pool and traverse fish pass at the Parteen regulating weir, a series of mark and recapture experiments were undertaken in 2008 and 2009.

The technique used to mark animals in mark and recapture studies has to be carefully selected and meet the assumptions that growth, survival, behaviour or capture probabilities of marked individuals are not affected, while the mark should be readable and retained for the duration of the study (Otis et al., 1978; Imbert et al., 2007). Tested methods for external and internal tagging and marking of anguillid species have mainly been developed for use on larger eels or do not allow individual identification (Thomassen et al., 2000; Simon and Dorner, 2005; Imbert et al., 2007). Tagging or marking eels can result in tag loss, infection, reduced growth or mortality primarily due to the eel’s ecology and behaviour, including its generally benthic and burrowing habit (Nielsen, 1988; McGovern and McCarthy, 1992b). The eel is particularly sensitive to tagging compared with other fish, with many eels dying or shedding tags within a short time after tagging. Some marking methods, such as panjet marking and colour baths have a less negative impact on eel growth and survival (Nielsen, 1988).

Imbert et al. (2007) evaluated visible implant elastomer marks on an ex-situ population of small European eels (59–240 mm \(L_T\)) in laboratory conditions as a method for individual marking and showed that it had no observed effect on the eels’ locomotor behavior and survival. The visible implant elastomer (VIE) mark (Northwest Marine Technology Inc., Shaw Island, WA, U.S.A.) is a two part, fluorescent coloured, silicone based material that is mixed before use. VIE is injected as a liquid that cures into a pliable, biocompatible solid. A hypodermic syringe is used to inject the VIE at a
shallow angle into transparent body tissue on the ventral side of the eel’s body between the anus and the base of the anal fin to reduce risk of damage to internal organs and minimise the potential marking effect on eel behaviour. VIE is available in ten colours and can be injected at a number of locations which allows for multiple marks to be created using different colour and location combinations. In this study the VIE marking method was used for the first time on juvenile eels in Ireland to estimate the efficiency of the juvenile eel trap at Parteen.

6.2.2 Methods and Materials

Eels from the Parteen juvenile eel trap were anesthetised using a 10:1 solution of ethanol (70%) and clove oil (Durif et al., 2006) to aid handling and minimise distress (Durif et al., 2006). All eels were measured for length to the nearest millimetre on a measuring board. The VIE mark was injected at a shallow angle into transparent body tissue on the ventral side of the eel’s body between the anus and the base of the anal fin (Imbert et al., 2007). After marking the eels were placed in aerated water until full recovery, which was assessed by exhibition of swimming behaviour. A different body location (Figure 6.6) or colour was marked on each day that eels were released in order to differentiate between released groups. A code was designated to each batch of eels released according to the colour used and the body location of the mark. Eels were released in the evening between 1700 and 1800 hours.

In 2008 one mark and recapture experiment was conducted with eels released on three consecutive days below the entrance of the Parteen juvenile eel trap, starting on August 20th. Three separate mark and recapture experiments were carried out in 2009, two occurring in July and the third in August. In the first two experiments that were conducted in 2009 on July 8th and 9th respectively the marked eels were released below the entrance of the Parteen trap. In the third experiment carried out on August 6th 2009, the eels were separated into six groups, with each group given a unique mark and released at locations in the river channel below the Parteen regulating weir including below the entrance of the Parteen trap (Figure 6.5).
Eels captured in the juvenile eel trap following the release of marked eels were examined visually for the presence of a VIE mark. Eels were anesthetised as described above to aid handling and minimise distress. A VI light (Northwest Marine Technology) which radiates a deep violet light (405 nm) that causes the VIE colours to fluoresce, increasing visibility of the mark, was used when inspecting eels for the presence of a mark.

Figure 6.5 Locations below the Parteen regulating weir at which six batch marked groups of juvenile eels were released on the 6/8/09
Figure 6.6 Locations of visible implant elastomer marks on the ventral side of *Anguilla anguilla*. Adapted from Imbert et al. (2007)

Figure 6.7 Manual injector and syringe for VIE marking

Figure 6.8 A juvenile eel with an orange coloured VIE mark
6.2.3 Results

In 2008 three mark and recapture experiments were conducted. The total sample size was 1000 eels, of which 152 were subsequently recaptured (15.20%). A summary of the data is presented below in Table 6.6. A percentage length frequency distribution of eels marked and subsequently recaptured is shown below in Figure 6.9. The mean length data for the released and recaptured eels are summarised in Table 6.7. There was no significant difference in total length ($L_T$) of eels released and recaptured (Kruskal-Wallis ANOVA, $p > 0.05$).

Table 6.6 Mark and recapture summary of results 2008

<table>
<thead>
<tr>
<th>Date of release</th>
<th>No. released</th>
<th>No. recaptured</th>
<th>% Recaptured</th>
</tr>
</thead>
<tbody>
<tr>
<td>20/8/08</td>
<td>250</td>
<td>37</td>
<td>14.80</td>
</tr>
<tr>
<td>21/8/08</td>
<td>400</td>
<td>65</td>
<td>16.25</td>
</tr>
<tr>
<td>22/8/08</td>
<td>350</td>
<td>50</td>
<td>14.28</td>
</tr>
<tr>
<td>Total</td>
<td>1000</td>
<td>152</td>
<td>Average = 15.20%</td>
</tr>
</tbody>
</table>
Figure 6.9 Percentage length frequency distributions of eels marked and recaptured at Parteen in 2008

Table 6.7 Descriptive statistics for lengths (mm) of eels released and recaptured at Parteen in 2008

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Released</td>
<td>1000</td>
<td>153</td>
<td>87</td>
<td>293</td>
<td>31</td>
</tr>
<tr>
<td>Recaptured</td>
<td>152</td>
<td>154</td>
<td>102</td>
<td>272</td>
<td>29</td>
</tr>
</tbody>
</table>

An analysis of the time between release and recapture for eels marked at Parteen in 2008 showed that 90.78% were recaptured within the first 5 days, with 98.68% being caught within the first 18 days of release. The longest time between release and recapture was 72 days.

In 2009, three separate mark and recapture experiments were conducted. The first two experiments were carried out on July 8th and July 9th and the sample size for these two experiments was 200 and 211 eels respectively. The eels were released adjacent to the Parteen trap, the same location as in the previous year’s experiment. 25 eels were
subsequently recaptured in the Parteen juvenile eel trap. 12 eels originating from the sample released on the first date and 13 from the second release date. An average of 77% of the total catch was examined to detect marked eels following the two release dates and an estimated percentage recapture rate of 12.64% and 8.53% was calculated. A summary of the data is presented below in Table 6.8.

Table 6.8 Summary of results of mark and recapture experiment where eels were released adjacent to the Parteen trap entrance

<table>
<thead>
<tr>
<th>Date of release</th>
<th>No. released</th>
<th>No. recaptured</th>
<th>Estimated% recaptured</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/7/09</td>
<td>200</td>
<td>12</td>
<td>12.64</td>
</tr>
<tr>
<td>9/7/09</td>
<td>211</td>
<td>13</td>
<td>8.61</td>
</tr>
<tr>
<td>Total</td>
<td>511</td>
<td>35</td>
<td>Average = 10.63</td>
</tr>
</tbody>
</table>

The third mark and recapture experiment of 2009 was carried out on August 6th. The total sample size was 303 eels. These eels were divided into 6 groups and each group was given an individually recognizable mark. 100 eels were marked and released below the entrance of the Parteen juvenile eel trap as in the previous experiments and the remaining 203 eels were released in 5 groups at locations downstream of the Parteen regulating weir (Figure 6.6). All of the eels subsequently captured in the Parteen juvenile eel trap were examined for the presence of marked eels. The recapture results for the groups of eels released below the trap entrance downstream of the Parteen regulating weir are shown in Table 6.9.
Table 6.9 Summary of results of mark and recapture experiment where eels were released adjacent to the Parteen trap entrance and downstream (d/s) of the Parteen regulating weir, 6/8/09

<table>
<thead>
<tr>
<th>Mark Code</th>
<th>Release location</th>
<th>No. released</th>
<th>No. recaptured</th>
<th>% Recaptured</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR5</td>
<td>Adjacent to trap</td>
<td>100</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>RR10</td>
<td>d/s of weir</td>
<td>40</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RL5</td>
<td>d/s of weir</td>
<td>40</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RL10</td>
<td>d/s of weir</td>
<td>43</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BL5</td>
<td>d/s of weir</td>
<td>40</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BL10</td>
<td>d/s of weir</td>
<td>40</td>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>303</td>
<td>11</td>
<td>Average = 2.08</td>
</tr>
</tbody>
</table>

A description of the length data for the released and recaptured eels is summarised in Table 6.10. The length data for the eels released and recaptured was not normally distributed (Kolmogorov-Smirnov Test, p < 0.05). There was a significant difference in the total length ($L_T$) of eels released and recaptured (Mann-Whitney $U$-test, p < 0.05). A percentage length frequency distribution of eels marked and recaptured is presented below in Figure 6.10. From the data presented in Table 6.10 and Figure 6.10 it is clear that the size range of eels recaptured is smaller than that of the eels that were released. In 2009 70% of recaptures occurred within 2 days of release and the longest time between release and recapture of an eel was 9 days.

Table 6.10 Descriptive statistics for the lengths (mm) of eels released and recaptured at Parteen in 2009

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>Median</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Released</td>
<td>714</td>
<td>142</td>
<td>138</td>
<td>85</td>
<td>289</td>
<td>35</td>
</tr>
<tr>
<td>Recaptured</td>
<td>37</td>
<td>149</td>
<td>146</td>
<td>111</td>
<td>198</td>
<td>23</td>
</tr>
</tbody>
</table>
Figure 6.10 Percentage length frequency distributions of eels marked and recaptured at Parteen in 2009
6.2.4 Discussion
In 2008 the recapture rates from the three mark and recapture experiments did not vary greatly (Table 6.6) and the average recapture rate of the three release events was 15.20%. There was no significant difference in the size of eels released and recaptured which implies that the use of VIE is appropriate as it does not adversely affect the behaviour of different sizes of eels.

In the mark and recapture experiments carried out in 2009 the recapture rates for eels released adjacent to the Parteen trap entrance were 12.64%, 8.61% (Table 6.8) and 10% (Table 6.9). The recapture rate for eels released in the river channel below the Parteen regulating weir was less than 2%, with no eels recaptured from four out of the five groups (Table 6.9). This result suggests that many juvenile eels migrating upriver do not encounter the attraction flow of the Parteen pool and traverse fish pass and the entrance of the juvenile eel trap. Placing an additional trap with sufficient attraction flow on the northern bank of the river opposite the existing trap would increase the likelihood of upriver migrating eels in that area of the river being trapped. There was a significant difference in the size of eels released and recaptured in 2009 with recaptured eels having a slightly larger mean size although the sample size was smaller than in the previous year.

Mark and recapture techniques have been used elsewhere to assess the effectiveness of elver passes and traps. In a similar mark and recapture study on the River Thames carried out from 1985 to 1987 (Naismith and Knights, 1988) recapture rates were highly variable (0 to 18.72%). The highest recapture rates (15.79 and 18.72%) were achieved from releases of marked eels early in the migratory season indicating that eels moving early in the season display the strongest migratory behaviour and so are likely to travel the greatest distance in one season. Some of the eels were recaptured up to 2 years after their release suggesting that they may not display migratory behaviour each year. In the present study no juvenile eels marked and released in 2008 were present in the eel
catches examined in 2009 but the low recapture rates in each experiment may also be a reflection of the variable tendency to migrate exhibited by individual eels (Naismith and Knights, 1988). In a three year study carried out on the River Severn and Avon in England recapture rates were low at only 2%, but of these recaptures only five eels from a total of 6418 had by-passed the traps on barriers between points of release and recapture suggesting that such traps are effective in sampling migrant eels but that migratory tendencies are highly variable (White and Knights, 1997a). In stocking studies undertaken in Denmark using unmarked eels (Berg and Jørgensen, 1994) the variable tendency of released eels to disperse upstream and downstream of release sites was observed. At the Parteen regulating weir, however, there is no alternative route for juvenile eels to ascend upstream past the weir as the water flow velocity in the pool and traverse fish pass is too high for migrating juvenile eels (Moriarty, 1986)(Chapter 7, this study).

The low average recapture rates suggest that a large proportion of potential migrants fail to locate or successfully use the trap, however, the trap catch provides a representative index of numbers of migrating juvenile eels. There may be scope for increasing the effectiveness of the eel trapping programme at Parteen by deploying additional traps in other suitable locations.
6.3 Electrofishing surveys on the lower River Shannon and River Lee

6.3.1 Introduction
In 2009 and 2010 electrofishing surveys were undertaken on the Shannon and Lee river systems downstream of hydroelectric power facilities in order to determine the size range and density of potential migrant juvenile eel populations present. Comparisons of the results obtained in relation to the lower River Shannon were made with those of McCarthy et al. (1994a) who undertook electrofishing surveys at a number of sites on the lower River Shannon as part of the Shannon Eel Management Programme 1992–1994.

In September of 2009 surveys were undertaken on the lower River Shannon, downstream of the Parteen regulating weir and on the Kilmastulla River which is a tributary of the River Shannon that joins downstream of the Parteen regulating weir. Four sites along the lower River Shannon, from the lower freshwater limit at the Lax weir to upstream of Castleconnell were electrofished. On the Kilmastulla River one site adjacent to the Parteen salmon hatchery was electrofished. In September 2010 an electrofishing survey was undertaken on the River Lee, approximately 180 metres downstream of the Inniscarra HPS.

6.3.2 Materials and Methods
Electrofishing was carried out using a light-weight battery powered electrofishing backpack unit (Safari Research Surveyor, Model 550-E) delivering 100Hz pulsed DC current at 200V. The cathode, a stranded metal wire, was trailed after the unit and the operator held the anode, a metal framed nylon mesh net with an insulated handle. An assistant using a dip net collected fish that failed to be captured by the operator. No stop nets were used as fishing was normally undertaken downstream of a natural barrier such as a riffle head. Fishing was carried out in an upstream direction, against the flow of water and all species of fish captured were retained in live well. All electrofishing
sweeps were undertaken on a timed basis, i.e. 20 minutes per fishing, in water depths which could be waded (up to 0.5 metres). The characteristics of the site were noted and data recorded on water temperature, conductivity, water depth, area fished, substrate type and details on fish other than eels present at the site.

Fish from each electrofishing sweep were held in live wells outside the sampling section until each electrofishing sweep was completed. The fish from each electrofishing sweep were sorted and processed separately. They were anaesthetised using a 10:1 solution of ethanol (70%) and clove oil (Durif et al., 2006). All fish species present were identified and measured for length to the nearest millimeter and were weighed to the nearest gram using an electronic balance. Fish were held in a large bin of aerated water after processing until they were fully recovered and then returned to the sampling section.

When possible, the multiple removal/depletion technique proposed by Moran (1951) and Zippin (1958) was used to provide an index of abundance for eels. Under this removal model, the declining catch of fish between multiple electrofishing sweeps is used to calculate capture efficiencies and abundance estimates. A minimum of two electrofishing sweeps must be performed although three or more electrofishing sweeps are recommended so that catchability assumptions can be tested (Temple and Pearsons, 2007).

The following steps were used in the estimation of population size from data collected in a multiple removal/depletion protocol, employing constant electrofishing effort (Zippin, 1958).

In the case of two electrofishing sweeps;
\[ \hat{N} = \frac{y_1^2}{y_1 - y_2} \]

where \( \hat{N} \) is the estimate of population size and \( y_1 \) and \( y_2 \) are the numbers of fish captured during the first and second electrofishing sweeps, respectively.

The formula for the standard error of this population estimate is:

\[ SE(\hat{N}) = \frac{(y_1)(y_2)\sqrt{y_1 + y_2}}{(y_1 - y_2)^2} \]

In the case of \( k \) electrofishing passes;

\[ \hat{N} = \frac{\text{Total catch}}{\text{Estimated proportion of population captured}} = \frac{T}{(1 - \hat{q}^k)} \]

Where \( \hat{N} \) is the estimate of population size and \( (1 - \hat{q}^k) \) is the estimated proportion of the population captured.

The formula for the standard error of \( \hat{N} \) is:

\[ SE(\hat{N}) = \sqrt{\frac{\hat{N}(\hat{N} - T)T}{T^2 - \hat{N}(\hat{N} - T)}} \cdot \frac{(kp)^2}{(1-p)} \]

A second population estimate was derived using the least squared regression described by Dixon and Massey (1951) cited by Zippin (1958).
6.3.3 Results

Electrofishing survey on the lower River Shannon

From the results of the 1993 survey (Table 6.11) the very high eel densities and the contribution of eels to the overall fish biomass in the lower River Shannon are evident. Eels were captured at a rate of 0.27 up to 4 eels per minute of fishing and eel density ranged from 0.01 to 0.955 eels/m² or 0.125 g/m² to 44.968 g/m². The results of the 2009 survey show the capture rate for eels ranged from 0.3 to 2.2 eels per minute and eel density ranged from 0.05 to 0.81 eels/m² or 0.145 g/m² to 16.44 g/m² (Table 6.12). In 1993 the density and biomass values resulted in eels comprising 54–92.5% of the total number of fish present and 81.6–98.5% of the total fish biomass (Table 6.11). Similar results were obtained in the 2009 survey with eels comprising 65–94% of the total fish numbers and up to 99% of the total fish biomass, except at the Angler’s Rest site where eels accounted for 30% of the total fish biomass (Table 6.12). At the Angler’s Rest site, dace Leuciscus leucisus(L.) accounted for 12% of the total fish numbers and 52% of the total fish biomass (Table 6.13, Figure 6.11). The mean length of eels captured in 1993 ranged from 195.7 mm to 302 mm (Figure 6.12 and Figure 6.13) and in 2009 the mean size ranged from 162 mm to 268 mm (Figure 6.14). No eels greater than 400 mm in length were present at any of the sites in 2009 and at only one site, Lax weir 2, were there eels smaller than 100 mm present.

An index of eel abundance for the area fished at the Angler’s Rest on the River Shannon and the Kilmastulla River at the Parteen salmon hatchery where three electrofishing sweeps were completed was calculated. The index was calculated using the multinomial method described by Zippin (1958) and the least squared regression method. For the Angler’s Rest site the index of abundance ± 2(SE) from the Zippin method was 68 ± 2(1.58), while at the Kilmastulla site it was 44 ± 2(5.72). These estimates are similar to those calculated using the regression method (Figure 6.16 and Figure 6.17).
Table 6.11 The results of eel electrofishing surveys in seven sites on the lower River Shannon, 1993

<table>
<thead>
<tr>
<th>Site</th>
<th>Area fished (m²)</th>
<th>Fishing duration (minutes)</th>
<th>Total fish</th>
<th>Total fish</th>
<th>% Eels</th>
<th>Eel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lax weir 1</td>
<td>272</td>
<td>29</td>
<td>108</td>
<td>2266</td>
<td>0.397</td>
<td>8.331</td>
</tr>
<tr>
<td>Lax weir 2</td>
<td>396</td>
<td>15</td>
<td>28</td>
<td>252</td>
<td>0.071</td>
<td>0.636</td>
</tr>
<tr>
<td>Lax weir 3</td>
<td>416</td>
<td>15</td>
<td>5</td>
<td>60</td>
<td>0.012</td>
<td>0.144</td>
</tr>
<tr>
<td>Clairville</td>
<td>225</td>
<td>15</td>
<td>63</td>
<td>3347</td>
<td>0.28</td>
<td>14.876</td>
</tr>
<tr>
<td>Castleconnell</td>
<td>116</td>
<td>20</td>
<td>72</td>
<td>1650</td>
<td>0.621</td>
<td>14.224</td>
</tr>
<tr>
<td>Pa's Gap</td>
<td>150</td>
<td>20</td>
<td>92</td>
<td>4874</td>
<td>0.613</td>
<td>32.493</td>
</tr>
<tr>
<td>Lackagh</td>
<td>78</td>
<td>20</td>
<td>107</td>
<td>3764</td>
<td>1.381</td>
<td>48.568</td>
</tr>
</tbody>
</table>

Table 6.12 The results of eel electrofishing surveys in four sites on the lower River Shannon and the Kilmastulla River, 2009. (* figures in brackets denote 2nd and subsequent fishing durations, all calculations are based on the first fishing)

<table>
<thead>
<tr>
<th>Site</th>
<th>Area Fished (m²)</th>
<th>Fishing duration (minutes)</th>
<th>Total Fish</th>
<th>Total Fish</th>
<th>% Eels</th>
<th>Eel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lax weir 1</td>
<td>180</td>
<td>20(20)*</td>
<td>17</td>
<td>272</td>
<td>0.09</td>
<td>1.511</td>
</tr>
<tr>
<td>Lax weir 2</td>
<td>54</td>
<td>20</td>
<td>47</td>
<td>896</td>
<td>0.87</td>
<td>16.6</td>
</tr>
<tr>
<td>Angler's Rest</td>
<td>95</td>
<td>20(20,20)*</td>
<td>46</td>
<td>1099</td>
<td>0.48</td>
<td>11.568</td>
</tr>
<tr>
<td>Castleconnell</td>
<td>126</td>
<td>20</td>
<td>7</td>
<td>270.8</td>
<td>0.05</td>
<td>2.14</td>
</tr>
<tr>
<td>Kilmastulla</td>
<td>210</td>
<td>20(20,20)*</td>
<td>90</td>
<td>1552</td>
<td>0.42</td>
<td>7.39</td>
</tr>
</tbody>
</table>
Table 6.13 Data on all fish species captured during electrofishing surveys on the lower River Shannon, 2009

|                | No. | Wt (g) | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt | No. | Wt |
|----------------|-----|--------|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|
| Lax weir 1     | 13  | 377    | 0   | 0  | 0   | 0  | 1   | <1 | 0   | 0  | 0   | 0  | 0   | 0  | 0   | 1  | 8   | 4  | <2 | 0  | 0  | 19  | 387 |
| Lax weir 2     | 44  | 888    | 0   | 0  | 0   | 0  | 0   | 0  | 2   | 2  | 1   | 6  | 0   | 0  | 0   | 0  | 0   | 0  | 0  | 0  | 0  | 47  | 896 |
| Angler’s Rest  | 58  | 597    | 5   | 62 | 0   | 0  | 0   | 0  | 2   | 24 | 7   | 6  | 0   | 0  | 0   | 0  | 0   | 0  | 0  | 10  | 852 | 1   | 2   | 83  | 1624|
| Castleconnell  | 6   | 256    | 0   | 0  | 0   | 0  | 0   | 0  | 0   | 0  | 0   | 0  | 0   | 0  | 0   | 0  | 0   | 0  | 0  | 1   | 16  | 0   | 0   | 7   | 272 |
| Kilmastulla    | 37  | 726    | 0   | 0  | 3   | 61 | 0   | 0  | 0   | 0  | 0   | 0  | 0   | 0  | 0   | 47 | 682 | 3   | 77  | 0   | 0  | 90  | 1546|
| Total          | 158 | 2844   | 5   | 62 | 3   | 61 | 1   | 0  | 2   | 24 | 9   | 8  | 48  | 688| 3   | 77 | 1   | 8  | 15  | 868 | 1   | 2   | 246 | 4725|
Figure 6.11 Pie charts describing the proportional abundance of each fish species at the riverine sites electrofished in 2009
Figure 6.12 Percentage length frequency distributions of eels sampled by electrofishing in the lower River Shannon in 1993 (McCarthy et al., 1994a)
**Figure 6.13** Percentage length frequency distributions of eels sampled by electrofishing in the lower River Shannon in 1993 (McCarthy et al., 1994a)
Figure 6.14 Percentage length frequency distributions of eels sampled by electrofishing in the lower River Shannon, 2009
Figure 6.15 Percentage length frequency distribution of eels sampled by electrofishing on the Kilmastulla River

Figure 6.16 Eel population estimation for the Angler’s Rest electrofishing site by regression method
Figure 6.17 Eel population estimation for the Kilmastulla River electrofishing site by regression method
Electrofishing survey on the River Lee at Inniscarra

A sample of 118 eels was captured at the Inniscarra site following 3 electrofishing sweeps of 20 minutes duration in an area of 165 m$^2$. Eel density and biomass were calculated based on the data collected in the first electrofishing sweep and was 0.45 eels/m$^2$ and 1.63 g/m$^2$. The eels ranged in length from 100 to 253 mm with a mean ± SD of 134 ± 25 mm. A percentage length frequency distribution for the sample is shown in Figure 6.18 along with the percentage length frequency distribution for a sample of eels collected from the Inniscarra juvenile eel trap in July of the same year. The sample from the trap comprised of mainly elvers and small bootlace eels ranging in length from 81 to 152 mm with a mean ± SD of 114 ± 16 mm.

An index of eel abundance for the area fished was calculated using the multinomial method described by Zippin (1958) and the regression method. Using the Zippin method it was estimated at 131 ± 2(7.44) which was similar to that estimated using the least squared regression method (128) (Figure 6.19).
Figure 6.18 Percentage length frequency distributions of eels sampled by electrofishing in the River Lee below the Inniscarra HPS and collected from Inniscarra juvenile eel trap

![Percentage length frequency distributions](image)

**Figure 6.19** Eel population estimation for the River Lee electrofishing site at Inniscarra by regression method

![Eel population estimation](image)
6.3.4 Discussion

The dominance of the fish assemblages of the lower River Shannon by eels shown in the 1993 survey reflected the high level of natural recruitment that occurred at that time. Because the area was not suitable for commercial eel fishing operations, for either yellow or silver eels, it was recommended that the area could be exploited for lake stocking by trapping and/or electrofishing as it had the potential to produce a catch of up to two thousand juvenile eels in a day’s fishing undertaken by a three man crew (McCarthy et al., 1994a). In the present study eel was the dominant fish species (by numbers) of the fish assemblages present at all sites on the lower River Shannon and the Kilmastulla River (Table 6.12). At the Angler’s rest site, however, dace accounted for a considerable proportion of the total fish number and biomass recorded. Dace is an invasive species in Ireland and was first introduced to Ireland in 1889 to the Munster Blackwater where it remained confined to this river for almost 100 years. By 1994 Dace were present in the lower River Shannon, from Limerick to the Ardnacrusha dam. The presence of dace in high densities puts native species under pressure to compete for food and space and particularly affect salmonids which have similar habitat preferences (Caffery et al., 2007).

Eel density (eels/m²) and biomass (g/m²) estimates for electrofishing sites in the present study were broadly similar to those found in the 1993 survey (Table 6.11 and Table 6.12) but differences in the length frequency distributions of eels sampled from the two surveys were apparent (Figure 6.12 to Figure 6.15). In the present study eels less than 100 mm $L_T$ were absent at the majority of sites and only represented a small percentage of the samples when they occurred. A much wider size range of eels were present in the 1993 survey in comparison to the present survey also.

Estimates of eel population size for the area fished derived from both the multinomial method and the least squared regression method were similar where three electrofishing sweeps were conducted indicating the simple least squared regression method is
satisfactory. Eel density (0.45 eels/m²) and biomass (1.63 g/m²) estimates for Inniscarra site on the River Lee were within the observed range of estimates for sites on the River Shannon in the present study. Larger eels were present in the sample captured by electrofishing on the River Lee at Inniscarra than were captured in the juvenile eel trap at Inniscarra HPS (Figure 6.18). It is possible that the juvenile eel trap is not suitable for use by larger bootlace eels due to the size selectivity of the substrate type in the trap. However, the electrofishing sample was collected later in the year (September 1st) than the sample from the juvenile eel trap (July 20th) and it may be the case that the smaller juvenile eels had migrated through the Borland fish lift earlier in the migration season. An increase in the mean size migrating juvenile eels towards the end of the season has been reported on the River Thames in England (1997b) and similarly Matthews et al. (1999) noted that the arrival of larger bootlace eels in the juvenile eel trap on the River Erne indicated that the migration was coming to an end.
6.4 Experimental fishing for juvenile eels in the navigation lock at Ardnamurcha HPS

6.4.1 Introduction
In July 2008 experimental fishing using baited traps and fishing lines was undertaken in the Ardnamurcha navigation lock to determine if eels were present and investigate if eels were actively using the navigation lock as a migratory route upriver by ascending the two navigation chambers leading to the dam fore-bay above Ardnamurcha HPS. The upriver movement of fish through navigation locks has been documented for a number of species (Monan et al., 1970; Mallen-Cooper et al., 1992).

6.4.2 Materials Methods and Results
On the 15-7-08 four small net traps baited with oily fish were deployed in the middle chamber of the navigation lock at 4 pm. Two traps were deployed on each side of the navigation lock. The traps were lowered from the guard railings surrounding the navigation lock to the bottom of the navigation lock in 4.5 metres depth of water.

The traps were lifted on the morning of the 16-7-08 at 8.30 am. One eel measuring 180 mm in length and weighing 7 g was captured.

On the 17-7-08 four small net traps, four bucket-like traps, two pipe traps and two fry traps all baited with oily fish were deployed in the middle chamber of the navigation lock at 1600 hours. A long-line with 20 hooks baited with earthworms on leaders spaced 1.5 m apart was also set in the navigation lock. The water depth in the navigation lock was 4.5 m. Six of the traps were lowered from the guard railings surrounding the navigation lock on one side of the navigation lock with an equal distance between traps and the other six were lowered from the opposite side of the navigation lock. The long-line was set so that the first hook was set in an upriver corner.
of the lock and the line was laid across the navigation lock so the last hook was set in the downriver corner on the opposite side.

The traps and long-line were lifted on the morning of the 18-7-08 at 0830 hours. One eel measuring 152 mm in length and weighing 5 g was captured in a small net trap. One eel measuring 185 mm in length and weighing 9 g was caught on a baited hook. Two small flounder and 1 perch measuring 135 mm in length were also caught on baited hooks.

6.4.3 Discussion
The results of experimental trapping and long-line fishing were disappointing. Possible explanations for the poor capture rate of juvenile eels is that there were few eels in the navigation lock when the trapping was undertaken. In 2008 the total catch of eels was just 6.846 kg which is remarkably low compared to catches recorded at the trap in the late 1970s and the 1980s. In addition to this, the navigation lock is located on the south bank of the River Shannon and is connected to the tailrace of the hydropower station via a 150 m long canal. The navigation lock is used infrequently and it is likely that upriver migrating juvenile eels are more attracted to water discharge from the hydroelectric power station and the Borland fish lift and therefore avoid entering the canal leading to the navigation lock. Larinier (2002) noted that fish passage through navigation locks is generally fortuitous due to the typical location of navigation locks in relatively calm zones to allow boats to manoeuvre where attraction flows are low.
Chapter 7  Use of CCTV cameras to observe and survey migrating juvenile eels

7.1  Investigation of usage of the Parteen pool and traverse fish pass by upstream migrating eels

7.1.1  Introduction
Fish behaviour and movement was monitored at the weircrest of the lowermost pool of the fish pass at the Parteen regulating weir on the River Shannon using closed-circuit video over three 24 hour periods in June 2010. The primary objective was to determine if juvenile eels were entering the fish pass and using it as a migratory route upstream.

The fish pass used at Parteen is a pool type fish pass which consists of a series of pools in steps leading from the downstream face of the Parteen regulating weir into the Parteen reservoir. Concrete walls separating each pool have a weir which controls the water level in each pool and the water discharge in the pass. The pass is supplied with a constant water flow from the Parteen reservoir of c. 0.5 m$^3$ s$^{-1}$.

7.1.2  Methods and Materials
A high resolution (540TVL) manual focus video camera (Sony Super HAD, 9–22 mm lens) enclosed in a water-resistant housing was mounted in air overhead of the lowermost weircrest of the fish pass. Ambient light was sufficient to provide usable images during daylight. When ambient light decreased to 10 lux and below, illumination was automatically provided by 35 infra red led pieces, 8 mm in diameter located in the camera housing. The camera was powered using a 12 v 110 Ah battery. Video output from the camera was recorded using a 2.0 USB digital video recorder connected to a personal computer and the files were compressed and transferred to a hard drive. The camera operated continuously during the period of observation and the
date and time was recorded on each frame. A 15 minute video recording was reviewed from each hour of the sampling period recorded between 2100 to 0500 hours. Sampling was limited to these hours as it was expected that this would be the time when juvenile eels were most active. Diel periodicity in juvenile eel activity has been observed by a number of authors including McGovern and McCarthy (1992a) and Tesch (2003) who found that upstream migration occurs mainly at night and when 15 minute recordings from daylight periods were reviewed in this study no eels were observed.

When reviewing the recorded data, fish were identified, counted and classified as either passing upstream or downstream past the weircrest or as attempting to swim upstream past the weircrest. Eel, sea lamprey (*Petromyzon marinus*) and large salmonids could be identified with confidence from the video record due to the differences in the size and body shape (fusiform and anguilliform). Occasionally small (< 100 mm, approx.) fusiform shaped fish, possibly perch, roach fry or small salmonids, were observed at the weircrest but these were unidentifiable and omitted from analysis.

To assess the success of fish entering the fish pass, a value termed local efficiency ($E_L$), used by Haro and Kynard (1997), was calculated for each fish type, (eel, lamprey and salmonids) for each night of observation as follows;

$$E_L = \frac{N_U - N_D}{N_U} \times 100;$$

where $N_U =$ number of fish passed upstream of the weircrest, and $N_D =$ number of fish passed downstream.
7.1.3 Results

The results shown in Table 7.1 show that very little eel activity was observed. Over the total duration of video observations reviewed only two eels were identified. One eel moved downstream over the weircrest on June 18th and one eel moved upstream over the weircrest on June 29th. Similarly, very few salmonids were observed over the sampling period. On June 18th one large salmonid was observed going downstream over the weircrest. On June 28th one salmonid was observed ascending into the fish pass and two were observed going downstream on June 29th. The most common fish observed were lampreys and local efficiency for lampreys entering the fish pass ranged from 0.23 to 0.50 (Table 7.1). On June 18th and 19th lampreys were observed on 64 occasions attempting to ascend the weircrest and 13 lampreys were observed successfully ascending the weircrest (Table 7.2). During the same period 10 lampreys were observed going downstream. On the other dates relatively few observations of lampreys were made.

Table 7.1 Local efficiency of each fish group at the Parteen pool and traverse fish pass.
The number of fish ascending the weircrest is shown in parenthesis

<table>
<thead>
<tr>
<th>Date</th>
<th>Lamprey</th>
<th>Salmonids</th>
<th>Eel</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-19th June</td>
<td>0.23 (13)</td>
<td>*1 downstream</td>
<td>*1 downstream</td>
</tr>
<tr>
<td>25-26th June</td>
<td>0.50 (4)</td>
<td>None observed</td>
<td>None observed</td>
</tr>
<tr>
<td>28-29th June</td>
<td>0.50 (1)</td>
<td>-1.00 (1)</td>
<td>1.00 (1)</td>
</tr>
</tbody>
</table>

Table 7.2 Observed activity of lampreys at the Parteen pool and traverse fish pass

<table>
<thead>
<tr>
<th>Date</th>
<th>Failed attempted to ascend</th>
<th>Successful ascent</th>
<th>Descent</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-19th June</td>
<td>64</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>25-26th June</td>
<td>1</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>28-29th June</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
7.1.4 Discussion

From the results it is apparent that eels did not use the pool and traverse pass frequently; however, one eel was observed successfully entering the fish pass indicating that the fish pass is not an obstacle to all migrating eels. On the dates when video recordings at the fish pass were made, juvenile eel catches in the Parteen trap ranged from 1.0 to 2.7 kg per night and the majority of the total juvenile eel catch for 2010 was made in June. It is likely that the current velocity in the fish pass is too strong for the majority of eels and therefore they do not attempt to ascend it. Similarly very few salmonids were observed using the pass although the fish pass has proven to be effective for returning adult Atlantic salmon which are captured in a trap in an upstream pool in the pass.

The most frequent observation was of sea lampreys attempting to ascend the weircrest of the pass. The lower River Shannon is an important location for sea lampreys and late May and throughout June is reported to be the period when the upriver spawning migration occurs (Igoe et al., 2004). The most common observation was the failed attempts by lampreys to ascend the weircrest indicating that they were unable to progress against the water flow. It is possible that relatively few lampreys made numerous repeated attempts to ascend the weircrest, however, the low local efficiency estimate for the period 18–19th June also supports the indication that the fish pass is not suitable to facilitate upstream migration of lampreys.
7.2 Diel pattern of activity of juvenile eels at the Parteen trap

7.2.1 Introduction
A closed-circuit video camera was used to record juvenile eels entering the holding tank of the Parteen juvenile eel trap (described in Chapter 3) in order to determine if a diel activity pattern was evident.

7.2.2 Methods and Materials
A high resolution (540 TVL) manual focus video camera (Sony Super HAD, 4–9 mm lens) enclosed in a water-resistant housing was mounted opposite the top of the ramp where it enters the holding tank of the trap. Infra-red lighting capabilities, power supply and recording equipment were identical to those described in section 7.1.2 above. An 8 minute video recording (equivalent to one 32 MB data file) was reviewed from each hour of the sampling period recorded which began at 0600 hours on August 5th and ended at 0600 hours on August 8th 2010. Counts of eels were made when eels were flushed into the holding tank of the trap from the top of the climbing ramp by the horizontal spray bar.

The times of astronomical dusk, sunset, astronomical dawn and sunrise were obtained from U.S. Naval Observatory (http://www.usno.navy.mil/) and the observation period sampled was separated into 4 categories; dawn, day, dusk and night. Astronomical dawn is the time at which the sun is 18 degrees below the horizon in the morning and is that point in time at which the sun starts lightening the sky. Prior to this time, the sky is completely dark. Astronomical dusk is the time at which the sun is 18 degrees below the horizon in the evening and at this time the sun no longer illuminates the sky.
7.2.3 Results

The highest numbers of juvenile eels counted entering the trap on the first two dates were recorded at dusk and on the third date, August 7\textsuperscript{th}; the highest numbers were counted during the night (Figure 7.1). No eels were recorded entering the trap during the day on August 5\textsuperscript{th} and on the other two dates a small number of eels were counted during the day (3 and 6 eels on August 6\textsuperscript{th} and 7\textsuperscript{th} respectively). Overall, the percentage of eels counted entering the trap during the day was 2\% of the total number of eels counted on the 3 sampling dates. 82\% of eels counted entered the trap during dusk and at night while 15\% were counted during the dawn (Figure 7.2). On the first two dates analysed, the majority of eels (52\% and 53\% respectively) were counted between 2100 and 0000 hours while on the third date 34\% of eels were counted for the same period (Figure 7.3).

Figure 7.1 The number of eels counted entering the holding tank at the Parteen juvenile eel trap during daytime, dusk, night-time and dawn on 3 dates in August 2010 (N = 363)
Figure 7.2 The percentage of eels counted entering the holding tank at the Parteen juvenile eel trap during day, dusk, night and dawn on 3 dates (combined) in August 2010 (N = 354)

Figure 7.3 The number of eels counted in each hour sampled between dusk and dawn on 3 dates in August 2010 (N = 354)
7.2.4 Discussion

A diel periodicity in activity was observed with 98% of juvenile eels entering the trap between the hours of 2100 and 0600 hours (or approximately the start of dusk and the end of dawn). It is likely that this behaviour is employed in order to avoid predation. On the first two dates the highest numbers of eels were counted during dusk and the numbers counted during the night and at dawn were progressively smaller. This trend prevailed when the data for the 3 dates were combined (Figure 7.2). Diel periodicity in juvenile eels has also been observed by McGovern and McCarthy (1992a) and Tesch (2003). In the study undertaken by McGovern and McCarthy (1992a) at a site just upstream of the saltwater wedge in the River Corrib they found that in excess of 96% of the catches of elvers collected at brush traps were taken during the hours of darkness. Tesch (2003) observed juvenile eels using a trap on the River Elbe and found that differences between day and night migrations were not so substantial. He noted that upstream migration during daytime can predominate if the proportion of glass eels that has immigrated in the same year is large. Tesch (2003) also compared the length frequency distributions of juvenile eels captured during day and night and found that the proportion of large juvenile eels captured is relatively higher at night than during the day and he surmised that, with increasing body length, juvenile eels change from initial 24 hour to night-time activity.

Diel periodicity in the activity of yellow stage eels has been reported elsewhere. In telemetric studies undertaken by Baras et al. (1998) on yellow eels (mean length 591 mm) they found that the radio-tagged eels almost exclusively moved at night and always ended their activity before sunrise, although some eels did leave their diurnal residence under low light conditions. McGovern and McCarthy (1992b) found evidence through tracking of radio-tagged yellow eels in the Corrib catchment that diurnal swimming speeds of eels during overcast weather were similar to those recorded during night-time. Nocturnal activity rhythms of small and large eels have been demonstrated in studies on other species of eels in the field (Jellyman and Sykes, 2003) and in laboratory settings (Glova and Jellyman, 2000) and the onset of activity at dusk has been related to feeding.
Chapter 8  Length, weight and pigmentation stage of juvenile eels sampled in estuarine areas

8.1  Introduction

The European eel’s lifecycle depends strongly on oceanic conditions where maturation, migration, spawning and larval transport are completed in the open ocean (Tesch, 2003; van Ginneken and Maes, 2005). The leptocephali larvae are transported by the Gulf Stream and North Atlantic Drift for a journey lasting less than one year to the coastal waters of Europe where they metamorphose to glass eels (Lecomte-Finiger, 1994; Arai et al., 2000).

“Glass eel” is the term given for developmental stages from completion of leptocephalus metamorphosis until full pigmentation. Hydrographic conditions are thought to influence the progression of larvae and early stage glass eels from the continental shelf to coastal waters and there is an argument for active glass eel migration in open seas which could explain why this early developmental stage manages to reach the coasts of the Mediterranean Sea and the Baltic Sea where different sea currents prevail (Tesch, 2003).

During estuarine migration glass eels use selective tidal stream transport (STST) until they reach the tidal limit of the estuary (McCleave and Wippelhauser, 1987). This migratory behaviour involves the glass eels ascending the water column at the beginning of the flood tide and maintaining their position in order to migrate with the current and then during ebb tides the glass eels would shelter near the bottom or in the sediment (McCleave and Kleckner, 1982).
The main aim of this investigation was to establish if changes in length, weight, condition factor and development of pigmentation of glass eels and elvers occurred in association with the latitudinal gradient along the west coast of Ireland. Four locations were chosen from which to collect samples of juvenile eels, with the furthest north being the Erne estuary and the most southerly being the Shannon estuary.

8.2 Study area

A detailed description of the Erne and Shannon river catchments is given in Chapter 2. In this investigation samples were also collected from the estuarine areas of the Erriff river catchment on the Galway-Mayo border and Corrib river catchment in county Galway (Figure 8.1).

The Corrib catchment area comprises of 3000 km\(^2\) and includes an extensive network of riverine and lacustrine habitats of varying trophic status. The Corrib estuary is approximately 1 km long and flows south into Galway Bay. Juvenile eels were collected at Nimmo’s Pier (Figure 8.4) on the southern bank where the River Corrib enters Galway bay. The substrate at the site was composed of sand and stones ranging in size from 2 mm to 400 mm. The Erriff catchment covers an area of 167 km\(^2\) and the Erriff River flows into the Killary Harbour, a long fjord-like inlet. The river is acidic, oligotrophic and flows over non-calcareous geology. In the estuary of the Erriff River samples were collected 350 m downstream of the Aasleigh Falls where the river enters the Killary Harbour (Figure 8.3). The site comprised of a rocky shore with much of it covered by seaweed. The substrate at the site comprised of sandy-gravel and scattered rocks covered with sea weed.

In the Erne estuary samples were collected at Mall Quay (Figure 8.2) near the town of Ballyshannon. The site is situated approximately 300 m downstream of the bridge in the town on the northern bank of the river. The substrate at the site comprised of sandy-
gravel and scattered rocks. In the Shannon estuary samples were collected at Barrington’s Pier, county Clare (Figure 8.5, Plate 8.1) on the north bank of the river approximately 700 m downstream of Limerick Docks. The substrate at the site was mainly sand and earth with scattered rocks at the base of the pier.

Figure 8.1 Map of Ireland showing the location of estuaries where juvenile eels were sampled
Figure 8.2 A map of the Erne estuary showing the area where glass eels and elvers were sampled (23/4/09)

Figure 8.3 A map of the Killary Harbour showing the area where elvers were sampled at the mouth of the Erriff River (26/4/09)
Figure 8.4 A map of Galway city showing the area where glass eels and elvers were sampled (27/4/09)

Figure 8.5 A map of the Shannon estuary near Limerick city showing the area where glass eels and elvers were sampled (28/4/09)
Plate 8.1 View of the Limerick city looking upstream from Barrington’s Pier in the Shannon estuary
8.3 Materials and methods

Juvenile eels were collected in the inter-tidal zone at each site at low tide during the new moon lunar phase in April 2009 when the tidal ranges at the sampling sites were at their maximum. The eels were located by overturning rocks and stones where glass eels were sheltering underneath and then collected using a small hand net or a plastic forceps.

The individual lengths (to the nearest millimetre), weights (to the nearest 0.01 g) and Fulton’s condition factor \( (K) \) were recorded. The Fulton’s condition factor was calculated as follows:

\[
K = 10^3 \times \frac{W}{L^3}
\]

Where \( W \) is weight in grams and \( L \) is length in centimeters and \( 10^3 \) is the scaling constant.

This factor compares the weight of a fish with that expected from an isometric weight-length relationship and can be used to compare condition of fish within and between populations. Fish that are heavier than average for a particular length are considered to be in better condition.

Following examination under binocular microscope (Nikon SMZ 1500) at 10x magnification the eels were assigned to one of eleven pigmentation stages (Table 8.1) as described in Tesch (2003). Pigmentation stages are determined based on the development of subepidermal, external chromatophores and also the internal chromatophores of the larval phases.
Table 8.1 Development of pigmentation in *Anguilla anguilla* (Tesch, 2003)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Larva, fully grown leptocephalus</td>
</tr>
<tr>
<td>II</td>
<td>Semilarva, pigmentation on the posterior end of the spinal chord</td>
</tr>
<tr>
<td>III</td>
<td>Semilarva, pigmentation on the nerve chord becomes more extensive, skin pigment also seen at the tip of the caudal fin</td>
</tr>
<tr>
<td>IV</td>
<td>Semilarva, pigmentation on the nerve chord reaches the head</td>
</tr>
<tr>
<td>VA</td>
<td>Metamorphosis complete, eel-like form, no external pigment (glass eel) except for the caudal spot</td>
</tr>
<tr>
<td>VB</td>
<td>No pigment on the back, body or tail region, except for the skull, caudal spot and some rostral pigment</td>
</tr>
<tr>
<td>VIA₁</td>
<td>Development of pigmentation along the whole dorsum, post-anal dorsolateral pigment develops, post-anal, no clear mediolateral pigment</td>
</tr>
<tr>
<td>VIA₂</td>
<td>No pre-anal ventrolateral pigment. Post-anal development of mediolateral pigment</td>
</tr>
<tr>
<td>VIA₃</td>
<td>No pre-anal ventrolateral pigment. Clear pre-anal development of mediolateral pigment, post-anally over almost entire dorsum, pigment rows along the myosepta, and in places doubling of the mediolateral melanophores</td>
</tr>
<tr>
<td>VIA₄</td>
<td>Clear development of pre-anal ventrolateral pigmentation. Initially, in places, a doubling of the mediolateral melanophores in the pre-anal region, post anal pigment between the myosepta in the ventral region, and finally, similar changes in the pre-anal region</td>
</tr>
<tr>
<td>VIB</td>
<td>Pigment rows along the myosepta becoming indistinct. Lateral line still recognisable, as are the individual melanophores on the head, ‘cheek’, behind and below the eyes and on the lower jaw</td>
</tr>
</tbody>
</table>
8.4 Results

8.4.1 Length, weight and condition indices
The length frequency histograms for eels collected at each site are shown in Figure 8.6 and summary data is presented in Table 8.2. One large juvenile eel measuring 160 mm was present in the sample collected from the Erne site, however, the majority of eels collected there were less than 85 mm in length. At the Erriff site the mean size of the eels collected was larger than the other 3 sites, at 85 mm. At the Corrib and Shannon sites size range of eels collected were similar ranging from 64–81 mm and 64–98 mm respectively.

Weight frequency histograms are shown in Figure 8.7 and summary data is given in Table 8.3. At the Erne site weight ranged from 0.22 to 5.34 g (mean 0.43 g), however, most values were lower than 0.4 g. At the Erriff site the weight ranged from 0.27–1.47 g (mean 0.75 g). The weights recorded for eels collected at the Shannon and Corrib sites had a similar range and mean values of 0.30 and 0.29 g respectively.

Condition values ($K$) recorded ranged from a minimum of 0.38 for a stage VIA IV elver from the Shannon to a maximum of 1.38 for a fully pigmented stage VIB young eel from the Erriff (Table 8.4). Condition frequency histograms for each site are shown in Figure 8.8. At the Erne the mean value recorded was 0.90 and the second highest condition value overall was recorded from a stage VIB young eel collected at this site. The mean value for eels collected at the Erriff site was 1.11, higher than at the other three sites. Mean values recorded from the Corrib and the Shannon were similar (0.78 and 0.72 respectively), however, the range of values recorded in the Shannon was greater (0.38 to 0.99).
Figure 8.6 Length frequency histograms for juvenile eels collected at each site
Figure 8.7 Weight frequency histograms for juvenile eels collected at each site
Figure 8.8 Condition (K) frequency histograms for juvenile eels collected at each site
Table 8.2 Length (mm) summaries of juvenile eels collected in estuarine locations

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>N</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erne</td>
<td>23/4/09</td>
<td>49</td>
<td>72</td>
<td>61</td>
<td>160</td>
<td>14</td>
</tr>
<tr>
<td>Erriff</td>
<td>26/4/09</td>
<td>14</td>
<td>85</td>
<td>68</td>
<td>106</td>
<td>11</td>
</tr>
<tr>
<td>Corrib</td>
<td>27/4/09</td>
<td>45</td>
<td>72</td>
<td>64</td>
<td>81</td>
<td>4</td>
</tr>
<tr>
<td>Shannon</td>
<td>28/4/09</td>
<td>72</td>
<td>74</td>
<td>64</td>
<td>98</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 8.3 Weight (g) summaries of juvenile eels collected in estuarine locations

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>N</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erne</td>
<td>23/4/09</td>
<td>49</td>
<td>0.43</td>
<td>0.22</td>
<td>5.34</td>
<td>0.74</td>
</tr>
<tr>
<td>Erriff</td>
<td>26/4/09</td>
<td>14</td>
<td>0.75</td>
<td>0.27</td>
<td>1.47</td>
<td>0.38</td>
</tr>
<tr>
<td>Corrib</td>
<td>27/4/09</td>
<td>45</td>
<td>0.29</td>
<td>0.20</td>
<td>0.44</td>
<td>0.06</td>
</tr>
<tr>
<td>Shannon</td>
<td>28/4/09</td>
<td>72</td>
<td>0.30</td>
<td>0.14</td>
<td>0.72</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 8.4 Condition (K) of juvenile eels collected in estuarine locations

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>N</th>
<th>Mean</th>
<th>Min.</th>
<th>Max.</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erne</td>
<td>23/4/09</td>
<td>49</td>
<td>0.90</td>
<td>0.60</td>
<td>1.37</td>
<td>0.14</td>
</tr>
<tr>
<td>Erriff</td>
<td>26/4/09</td>
<td>14</td>
<td>1.11</td>
<td>0.77</td>
<td>1.38</td>
<td>0.20</td>
</tr>
<tr>
<td>Corrib</td>
<td>27/4/09</td>
<td>45</td>
<td>0.78</td>
<td>0.64</td>
<td>0.89</td>
<td>0.06</td>
</tr>
<tr>
<td>Shannon</td>
<td>28/4/09</td>
<td>72</td>
<td>0.72</td>
<td>0.38</td>
<td>0.99</td>
<td>0.11</td>
</tr>
</tbody>
</table>
8.4.2 Pigmentation

The extent to which juvenile eels at each site have developed pigmentation is shown in Table 8.5 and a frequency histogram shows the distribution of each of the pigmentation stages identified at the sampling sites (Figure 8.9). The results presented in Table 8.5 show that the extent of pigmentation is not determined by eel length for stages VB to VIAIV, however, the mean length of stage VIB eels was the largest at each site. The Erne and Shannon sites had the widest spread of pigmentation stages present and in each of these sites stage VIAII dominated the samples. Stage VIB eels were predominant in the small sample collected at the Erriff site while at the Corrib no stage VIB eels were recorded and the sample was dominated by stage VIAIII eels.

Table 8.5 The number, size range and mean length (mm) of juvenile eels in each of the pigmentation stages from each site

<table>
<thead>
<tr>
<th></th>
<th>VB</th>
<th>VIAI</th>
<th>VIAII</th>
<th>VIAIII</th>
<th>VIAIV</th>
<th>VIB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Erne</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>2</td>
<td>14</td>
<td>18</td>
<td>8</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Range</td>
<td>68-73</td>
<td>64-74</td>
<td>62-76</td>
<td>68-72</td>
<td>65-67</td>
<td>71-160</td>
</tr>
<tr>
<td>Mean</td>
<td>70</td>
<td>70</td>
<td>69</td>
<td>70</td>
<td>66</td>
<td>106</td>
</tr>
<tr>
<td><strong>Erriff</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>68-80</td>
<td></td>
<td></td>
<td>73-106</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>72</td>
<td>74</td>
<td></td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Corrib</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>1</td>
<td>14</td>
<td>28</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>69-82</td>
<td>64-81</td>
<td>72-76</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>67</td>
<td>74</td>
<td>71</td>
<td>74</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Shannon</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>2</td>
<td>8</td>
<td>20</td>
<td>19</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>Range</td>
<td>70-79</td>
<td>67-78</td>
<td>64-80</td>
<td>67-84</td>
<td>65-88</td>
<td>70-98</td>
</tr>
<tr>
<td>Mean</td>
<td>74</td>
<td>72</td>
<td>71</td>
<td>73</td>
<td>74</td>
<td>84</td>
</tr>
</tbody>
</table>
Figure 8.9 Frequency histogram of pigmentation stages for all eels from each site
8.5 Discussion

The length, weight, condition indices and pigmentation stages of juvenile eels from estuarine habitats are presented in the context of a wider study on the upriver migration of juvenile eels. There was no apparent association between changes in length, weight, condition value or pigmentation stage of eels collected from the four sites and their locations along the latitudinal gradient.

Eels from the Shannon and the Corrib were similar in respect to mean length, weight, condition factor and the range of pigmentation stages observed, although the size range of eels present in the Shannon sample was wider. The largest size range of eels was observed in the sample collected from the Erne but the largest mean length and weight values were calculated from the Erriff sample.

The mean condition value recorded for eels from the Erriff was greater than at the other 3 sites. The increase in mean length of the eels collected at the Erriff is associated with the higher condition value obtained. Fulton’s condition factor ($K$), increases with increasing length, limiting its application to fish of similar length within the same species (Guy et al., 2007). The condition values calculated for eels collected in the Corrib during this study are similar to those reported by McGovern and McCarthy (1992a) where condition values ranged from 0.63–0.93.

The extent of pigmentation was not determined by eel length a result that has been obtained in other studies (Wang and Tzeng, 2000). Haro and Krueger (1988) suggested that because development of pigment adapts pelagic glass eels to a benthic existence, increased pigmentation may be explained by increased contact with substrate.
The arrival of glass eels is known to occur throughout the year in groups known as “arrival waves” (Pujolar et al., 2006) and variations in glass eel recruitment abundance has been negatively correlated with the North Atlantic Oscillation suggesting that changing ocean conditions could be affecting recruitment (Friedland et al., 2007). Wang and Tzeng (2000) investigated the timing and metamorphosis of European eel elver by analysing samples collected from estuaries in Portugal, France, the United Kingdom, Ireland, and Sweden. They found that the mean length of European elvers increased from 65.0 to 66.8 mm in three mid-European countries but mean lengths in the north and south of its geographic range was similar at 68.0 mm.
Chapter 9  Overview and conclusions

This study was undertaken to improve knowledge on the biology and behaviour of juvenile eels migrating upstream in the Shannon, Erne and Lee river systems, each of which is harnessed for hydroelectricity generation. Since the 1980s the European eel population has declined significantly and causal factors of this decline that are frequently proposed include barriers to migration, loss of freshwater habitat and the effects of the swimbladder parasite Anguillicoloides crassus. In 2007 the European Commission published Council Regulation (EC) 1100/2007, establishing measures for the recovery of the eel stock requiring the implementation of an eel management plan in all member states that contain natural habitat of the European eel. The inclusion of monitoring plans to assess the trends of population parameters of the European eel is a necessary measure in order to adapt management actions to changes over time.

The abundance, seasonal duration and variation in timing of eel recruitment to Shannon, Erne and Lee river systems were examined (Chapter 3). Juvenile eels were also described in terms of length, weight and age of eels sampled during the migration season. Total catches varied between years at each trapping site and were generally low. Highest catches were made at the Parteen regulating weir on the River Shannon and there was a large interannual variability in the total catches which ranged from 139 to 1306 kg. The catches of elvers and juvenile eels at the Ardnacrusha dam on the River Shannon from 2008 to 2010 were remarkably low in comparison to peak catches recorded at this site in the past. However, they continued the pattern of variable but relatively poor catches observed in recent years. Similarly, at Cathaleen’s Fall on the River Erne total catches varied between years (from 36 to 94 kg), but were also relatively low. In the period 1970–2002 the average annual catch was 1300 kg at this site. On the River Lee the total annual catches were low at the trap installed at the Inniscarra dam. Prior to 2008 no trapping of migrating juvenile eels took place on the River Lee and recruitment to habitat upstream of the Inniscarra dam is thought to have
taken place via the Borland fish lift. Reasons for the variable and low total annual catch at the juvenile eel trap may be that its location in relation to the dam is not optimal and its effectiveness may be impaired as a result. Future monitoring of the catches may be beneficial in providing an index of recruitment to the area of the catchment upstream of the Inniscarra dam.

The timing and the duration of the juvenile eel migration showed great interannual variability and differences between sites. The date of the first capture of eels at the Parteen regulating weir on the River Shannon varied considerably in each year from May 8th in 2008 to June 8th in 2009 and similarly water temperatures on the date of the first recorded catch varied (13.8–17.5º C). First catches were made as early as April at Cathaleen’s Fall on the River Erne in 2010 and in each year the majority of the total catch was recorded before the end of July. In contrast, on the River Shannon at Parteen, the migration of juvenile eels continued until the end of October in 2008.

The influence of environmental factors on the variation in eel recruitment in the River Shannon at Parteen was analysed using multiple regression appropriate to time series data (Chapter 4). Clear cause and effect relationships were difficult to identify because a number of environmental factors may act in unison on the migration. The importance of these variables may vary with time and local hydrological and climatic conditions. In addition, lower eel densities observed with increased distance inland from the ocean contributes to the difficulty in assessing the impacts of environmental variables on upstream migration. In the present study a small but statistically significant amount of the variation in juvenile eel catch was explained by a number of environmental variables including day length, flow, water temperature, moon fullness and year. The most apparent evidence of the positive influence of river flow on the magnitude of the juvenile eel catch was in August 2008. An exceptional peak in catch coincided with unusually high river flow in the Kilmastulla River, a tributary of the lower River Shannon that joins the main river downstream of the Parteen regulating weir, following
very heavy rainfall. The catch recorded in August 2008 accounted for 51% of the total catch at Parteen for the period 2008 to 2010.

*Anguillicoloides crassus* is a parasitic Dracunculoid nematode and a natural parasite of the Japanese eel *Anguilla japonica*. Its introduction to Europe in the 1980s through transport of live eels has been suggested as one of the principal causes of the collapse of the European eel population. It was first recorded in Ireland from eels captured in the Waterford estuary in 1997 and it has since become well established in several Irish river systems. The results of an investigation of presence of *Anguillicoloides* in migrating juvenile eels were presented (Chapter 5). *Anguillicoloides* was not present in eels examined from the River Lee system; however, protection of the Lee eel stocks from *Anguillicoloides* and other pathogens that can affect the quality of eels is still very important and vigilance is necessary to ensure this. In the sample of eels examined from the River Erne both prevalence and intensity of infection were low in comparison to results from other studies on the same river system and this may be due to the different size class of eels examined or the differing habitat types where eels were collected. Mean prevalence of *Anguillicoloides* ranged from 23–66% in eels sampled from the River Shannon. Mean prevalence of *Anguillicoloides* in juvenile eels sampled from Parteen appeared quite stable however the fluctuations in mean prevalence in eels (predominantly elvers) from Ardnacrusha may be caused by a number of factors such as variations in eel or intermediate host density and lower parasite transmission rate in waters with higher salinity. There was no significant correlation between the number of *Anguillicoloides* present and Fulton’s condition factor (K) in eels sampled at either Ardnacrusha or Parteen and infected eels were typically in good condition. The occurrence of *Anguillicoloides* in juvenile eels migrating upriver in the Shannon and Erne systems highlights another dispersal route of this parasite. It also has implications for the choice of stocking strategy selected if, in the event of recovering recruitment, “surplus” recruits will be stocked to good quality catchments free of *Anguillicoloides*. 
The size selectivity and performance of new juvenile eel traps using different substrate types located at the Parteen regulating weir was investigated and compared to the existing trap to determine if an increased size range of upriver migrating eels could be collected through the use of alternative substrate types (Chapter 6). The need for a range of substrate types to facilitate the wide size range of eels migrating upstream and the importance of the location of a trap to its effectiveness was highlighted. Providing additional traps at optimal locations, close to the weir and major attraction flows where eels are more likely to congregate, could also improve the effectiveness of the trapping program.

The efficiency of the juvenile eel trap used at the Parteen regulating weir was investigated using a series of mark and recapture experiments with VIE marks in 2008 and 2009 (Chapter 6). In 2008 the recapture rates from the three mark and recapture experiments (where eels were released adjacent to the trap) did not vary greatly and the average recapture rate was 15.20%. There was no significant difference in the length frequency distribution of eels released and recaptured suggesting that the use of VIE is appropriate as it does not adversely affect the behaviour of different sizes of eels. In 2009 the recapture rates for eels released adjacent to the Parteen trap entrance ranged from 8.61 to 12.64%. The recapture rate for eels released in the river channel further below the Parteen regulating weir was less than 2% and the low average recapture rates overall suggest that a large proportion of potential migrant eels fail to locate or successfully use the trap. It also suggests there may be scope for increasing the effectiveness the eel trapping programme below the Parteen regulating weir by deploying additional traps in suitable locations.

Fish behaviour and movement was monitored at the weircrest of the lowermost pool of the fish pass at Parteen on the River Shannon using closed-circuit video over three 24 hour periods in June 2010 to determine if juvenile eels were capable of using the pass as a migratory route upstream (Chapter 7). Closed-circuit video was effective in observing
eel and other fish species behaviour at the Parteen fish pass and it was apparent that eels did not use the pass frequently. However, one eel was observed successfully entering the fish pass indicating that the relatively high water velocity is not an obstacle to all upriver migrating eels. Sea lamprey *Petromyzon marinus* were frequently observed attempting to enter the pass unsuccessfully. Juvenile eels entering the holding tank of the eel trap at the Parteen regulating weir were observed using the same method in August 2010. A pronounced diel periodicity in the activity of juvenile eels was observed with 98% of juvenile eels entering the trap between the hours of 21:00 and 06:00 hrs (or approximately the start of dusk and the end of dawn). It is likely that this behaviour is employed in order to avoid predation.

The length, weight, condition factor and development of pigmentation of glass eels were examined from four sampling sites at different latitudes along the west coast of Ireland (Chapter 8). No relationship was found between changes in these parameters and the sampling location. Eels from the Shannon and the Corrib estuaries were similar in respect of each parameter, although the size range of eels present in the Shannon sample was wider. The condition values calculated for eels collected in the Corrib during this study are similar to those reported previously.
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